A novel fault diagnosis method of PV based-on power loss and I-V characteristics

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Abstract. The power loss and the changes of internal I-V output characteristics of photovoltaic (PV) module in the typical fault condition were analyzed. We proposed an on-line real time fault diagnosis method for PV module, which takes into account the power loss and the internal I-V characteristics. Taking into account the changes of temperature and irradiation, the running status of the PV module were simulated in real time. Firstly, by comparing the simulated power with the measured power, it could determine whether the abnormal power loss has occurred. Then based on the change of output voltage, it could decide if short-circuit fault has occurred and estimate the number of short circuited cells roughly. Further, the value of fill factor (FF) can be utilized to determine whether aging fault has occurred and to acquire the remaining service life of the module. The results of simulation and experiment show that this method can effectively detect the partial shadow short-circuit fault and aging fault. It proves the feasibility and accuracy of the fault diagnosis method.

1. Introduction

With the growing of global economy, primary energy resources such as coal, oil and natural gas have become increasingly scarce. Solar power is promoting and applying rapidly with the advantages of clean, pollution-free, unlimited and sustainability [1]. Generally, the working condition of PV power plant is poor, resulting in the continuous occurrence of different kinds of fault. Therefore, the monitoring of the operating states and fault diagnosis of the PV systems become more and more
important. For the moment, domestic and overseas scholars mostly were committed to the photovoltaic systems for large-scale power generation which is equipped with centralized inverter or series inverter. However, for small or medium power photovoltaic power generation system connected by micro inverter, there is no effective online fault detection system. In the small power photovoltaic system, each PV module is respectively connected with a micro inverter. When a module in the system cannot work normally, only this one will be affected, however, the other modules will work normally which makes system more efficient. Detecting and replacing module accurately in the running process of PV system can further improve the efficiency of the system.

Currently, there are several common fault diagnoses based on infrared picture analysis, based on electrical measurement, based on intelligent detection and based on monitoring system, respectively. Some authors took advantage of the thermic effect of photovoltaic cells to detect PV module by means of infrared technique [2-4]. By analyzing the characteristics of infrared images, the status of the PV module can be obtained. However the infrared images are easy to be affected by environment. A direct earth capacitance detection method was proposed to determine whether there is an open circuit fault and navigate to the cut point by measuring the earth capacitance of PV modules [5]. But this method can only detect the circuit fault. TDR was proposed to judge fault type and fault location by analyzing the signal reflected from the fault point [6]. A method for multi-sensor was proposed to judge fault type and fault location through analysis of voltage and current collected by the sensors [7]. By analyzing the power loss which is collected from the DC-side, it can realize fault diagnosis of PV module [8]. An online fault diagnosis strategy was proposed by Wang and Li [9], who use BP neural network to detect the fault accurately. This method has abilities of self-study and adaptive, associative memory and nonlinear pattern recognition. And it is suitable for multi fault and complex pattern recognition. At present, the application of intelligent detection method in fault diagnosis of PV system is not much. Bruno Andò [10] presented an intelligent monitoring system with the aim of detecting the causes of efficiency losses, which equipped with voltage, current, irradiance, temperature, and inertial sensors. Because of the high cost of the monitoring system, method based on the monitoring system isn’t suitable for small PV systems.

We propose a novel on-line real time fault diagnosis method for PV module, which takes into account the power loss and the internal I-V characteristics. Firstly, by comparing the difference between the simulated power and measured power, it could determine whether the abnormal power loss has occurred. Then identify the source of power loss based on the changes of radiation of the measuring points. What following is judging if short-circuit fault has occurred and estimating the number of short circuited cells roughly by the change of output voltage. If the aging fault occurs, analyze the fill factor and judge the degree of aging fault considering the temperature and solar light. If serious aging fault has occurred, replace the new photovoltaic module.

2. Analysis of common faults

Module failures happen easily with different kinds of faults because of the badly equipping environment of PV system. The fault criterion is determined by analyzing the output properties of different kinds of faults in detail and comparing with the output properties of normal module.
2.1 Fault type
PV module usually consists of multiple solar cells, as shown in figure 1. When one or more cells of PV module were shaded by surrounding buildings or trees, partial shadow will be formed. As shown in figure 1 (a). In theory each cell in PV module should be in parallel with a bypass diode. The main role of the bypass diode is to provide an additional current path so that the output power of PV module will not be affected when the cells are under the shadow or there is dust on the surface. But in practice, because of heating and the restriction of economy, usually a string which consists of 12 cells will be equipped with an anti-parallel diode. When the cells are in the shadow of occlusion, they show resistance properties. The diode will turn on and insulate the cell which fails to run from the PV module under forward bias voltage. Therefore partial shadow of PV module will cause a great loss of power. Faulty soldering and over welding in the process of production may cause the cells be short-circuited or disconnected, as shown in figure 1(b), figure 1(c).

The average lifespan for a PV module is 20 to 30 years. However, in practical application, because of the manufacturing processes and installation environment, PV module will appear abnormal aging fault after five to six years of operation, as shown in figure 1(d).

![Figure 1. Common faults of PV module.](image)

2.2 Effects of faults on the power loss and the I-V characteristics of PV module
For the purpose of studying the power loss of PV module with different shadow rate, an experiment was carrying out on the JHX250P60 PV module. The change of the power loss of module with different shadow rate is shown in figure 2 and table 1.

![Figure 2. Power loss of module with different shadow rate.](image)
Table 1. Power loss of module with different shadow rate.

| shadow ratio /% | Uoc/V  | Isc/A  | Pm/W  | Power loss rate/% |
|-----------------|--------|--------|-------|-------------------|
| 0               | 37.64  | 8.412  | 243.7948 | 0 |
| 5               | 37.05  | 6.391  | 186.4207 | 23.533 |
| 10              | 36.90  | 2.443  | 71.6658  | 70.604 |
| 20              | 33.25  | 0.031  | 0.4577   | 99.812 |
| 50              | 27.58  | 0.004  | 0.0130   | 99.998 |
| 80              | 14.46  | 0.001  | 0.0021   | 99.999 |

As is shown in figure 2 and table 1, the power loss shows a nonlinear increase with the increase of partial shadow rate. And the power loss rate of PV module is far larger than the partial shadow rate. When the shadow rate is up to 5%, the power loss rate exceed 20%; When the shadow rate is up to 10%, the power loss rate exceed 70%; When the shadow rate is up to 20%, the power loss rate exceed 99%, namely the output power approaches zero. The output power of PV module is affected by partial shadow seriously. When the shaded area is too large to meet the requirements of micro inverter, PV module will not continue to output power.

In order to study the influence of different types of faults on the output characteristics, we simulate and analyze in the case of faultless, partial shadow, short circuit and aging fault. The I-V characteristics of different faults are shown in figure 3.

![Figure 3. U-I curves under different faults.](image)

PV module which equipped with three bypass diodes consists of 36 cells in simulation. As is shown in figure 3, the I-V curve shows “multiple knees phenomenon” because of partial shadow. However the short-circuit current and the open-circuit voltage of module will not change. Short circuit fault causes the reduction of the open circuit voltage and the maximum power point voltage. The shape of the curve is as basically the same as the I-V curve in the absence of fault. In the case of aging fault, the maximum power point voltage ($U_{m}$) and the maximum power point current ($I_{m}$) reduce accordingly, but the open circuit voltage and short circuit current remain basically unchanged.

As is shown in figure 4, simulate different degree of aging by changing the internal series resistance of PV module. When the series resistance increases, namely the degree of aging increase, the I-V curve shape of PV module remained unchanged, but shows a tendency of contraction.
3. Fault diagnosis strategy

By analyzing the output power of faulty module, we learn that the abnormal power loss is likely to come from module failures. It is difficult to identify the fault simply by analyzing the power loss. Especially the changes of irradiation and temperature can also cause a high power loss which leads to misjudgment of the diagnosis system. We can identify some types of faults according to the internal characteristics changes of different types of faults. But it is difficult to identify the other faults because the changes of their internal characteristics are not so obvious. Therefore taking into integrative consideration the output power loss and the internal characteristics is helpful to improve the accuracy of fault diagnosis.

3.1 Diagnosis strategy of partial shadow

The micro inverter with a function of power recording plays an important role in timely detecting abnormal power loss and avoiding long-term work in fault state for PV module. An effective operation of a PV module is difficult to avoid power loss which includes the power loss caused by sun light incidence angle, the power loss caused by the temperature, the power loss cause by the inaccuracy of maximum power point tracking and the micro inverter switching loss etc. A brief description of the main factors in the conventional power loss of PV module is shown in figure 6. In the first part of power loss, the impacts of the incident angle, the reflecting of PV module and the dust make the irradiation of PV module different from the irradiation of simulation input, which causes the difference between the simulated power and measured power. Considering the general frequency of the cleanup, adopt 8% as the power loss rate. In the second part of power loss, the output voltage and the output current change with the change of the temperature which leads the reduction of output power. Therefore, the power loss caused by temperature is an important factor which should be considered. Generally, the average power loss rate of temperature is 3%. In the third part of power loss, the maximum power point tracking is accurate by default in the simulation model, namely the output power is the maximum power of the module. In practice, the most ideal tracking precision can reach 99.5% that result in some difference in the maximum power point power. In addition, there is a problem of the conversion efficiency of micro inverter. At present, the conversion efficiency of high quality micro inverse can reach 97.5% so that the power loss rate of the inverter efficiency is about 3%.

In order to determine whether the power loss is in the normal range, the boundary of daily power loss should be established firstly. As is shown in figure 7, the curve A is the actual output power curve of the experimental module without fault and the data were recorded during a sunny day in the summer of
2015. The curve B is the theoretical output power curve obtained from the simulation module which take the measured irradiation and measured temperature as its input variables. By comparing the measured power value of each measurement point with the theoretical value of the simulation, we can know that the normal power loss rate of the PV module without fault is generally between 13%-15%. If the power loss rate is more than 15%, it can be defined as abnormal power loss. Abnormal power loss may result from short circuit fault, aging fault and other faults, but also may come from partial shadow or the sudden decline of the irradiation caused by the cloud cover.

Therefore, it is also needed to determine whether the irradiation of the measuring point has been decreased abnormally in order to distinguish different faults. In the case of fine weather, the irradiations of two adjacent measuring moments are similar. So the irradiations of the first few measuring points can be used to get the irradiation of the next measuring point. \( S_n = \min \{ S_i, i = 1, 2, 3 \} \), where \( S_n \) is the constructed irradiation of the current measuring point, \( S_i \) are the irradiations of the first few measuring points. And \( S'_n \) is the measured irradiation of the current measuring point. If \( S_n - S_0 \leq S'_n \leq S_n + S_0 \) (\( S_0 \) is the margin for the variation), it can be judged as the normal irradiation change. If \( S'_n < S_n - S_0 \) is tenable within consecutive 30 minutes, it can be judged that partial shadow has occurred.

![Figure 5. Comparison of the simulated power and the measured power.](image)

### 3.2 Diagnosis strategy of short circuit fault

The output voltage of PV module will reduce when the circuit fault occurs. So it can decide if the short circuit fault has occurred by comparing the simulated output voltage with the measured output voltage. A variable \( \alpha \) is introduced as shown in equation (1).

\[
\alpha = \frac{V'_{oc} - V_{oc}}{V_{oc}}
\]  

(1)

Where \( V'_{oc} \) and \( V_{oc} \) are, respectively, the simulated open circuit voltage and the measured open circuit voltage, \( V_{oc} \) is the average open circuit voltage of the cells in PV module. If \( \alpha > 1 \), it can be determined that the short circuit fault has occurred. The number of the cells which are short circuited is determined by equation (2).
3.3 Diagnosis strategy of aging fault

In the classification of fault types, it is mentioned that the aging fault will result in the increase of series resistance. Direct measurement for internal series resistance of PV module is difficult and the accuracy is difficult to guarantee, so the fill factor which is easier to access to is introduced. The fill factor (FF) is a measure of the quality of solar cells (series resistance and shunt resistance). The fill factor (FF) is defined as the maximum output power divided by output power of ideal target \((I_{sc}\times V_{oc})\) as shown in equation (3).

\[
FF = \frac{I_{m}V_{m}}{I_{sc}V_{oc}}
\]  

It is clear that FF should be as close as possible to 1 (i.e.100%). But the characteristic of the exponential function p-n junction prevents it from reaching 1. The value of FF is affected by the series resistance. We can get the curve of the filling factor (FF) with the change of the series resistance from the simulation. The fill factor decreases with the increase of the series resistance non-linearly as shown in figure 7. In this paper, the value of the fill factor is used to judge the occurrence of aging fault and to determine the degree of aging.

![Figure 6. Curves of the fill factor with the change of resistance.](image_url)

In order to calculate the FF of normal module, the value of series resistance of the module without aging fault need to be estimated under standard test conditions.

\[
I = I_{ph} - I_{0}(\exp\left[\frac{q(V + IR_{s})}{AKT}\right]-1) - \frac{V + IR_{s}}{R_{sh}}
\]  

The output characteristic of PV cells is shown in equation (4). Where \(I_{ph}\) is the photocurrent of the cell, \(I_{0}\) is the reverse saturation current of the cell, \(V\) is the output voltage of the cell, \(q\) is the charge constant, which general is \(1.6\times10^{-19}\) C, \(A\) is the diode factor, \(K\) is the Boltzmann's constant, which is \(1.38\times10^{-23}\) J/K, \(T\) is absolute temperature in K, \(R_{s}\) and \(R_{sh}\) are, respectively, the series resistance and the parallel resistance of PV cells. Generally the parallel resistance (\(R_{sh}\)) of PV cells is very large...
which makes the value of $\frac{V + IR_s}{R_{sh}}$ far less than the photocurrent. So the value of $\frac{V + IR_s}{R_{sh}}$ can be neglected. Equation (4) can be simplified as equation (5).

$$I = I_{ph} - I_0 \left\{ \exp\left[\frac{q(V + IR_s)}{AKT}\right] - 1 \right\}$$  \hspace{1cm} (5)

The “-1” can be neglected in equation (5) because the value of $\exp\left[\frac{q(V + IR_s)}{AKT}\right]$ is far large than 1. The equation (6) can be obtained by setting conditions of $I_{ph} \approx I_{sc}$ and $\lambda = \frac{q}{AKT}$.

$$I = I_0 \left[1 - \left(\frac{I_0}{I_{sc}}\right) \exp\left(\lambda (V + IR_s)\right)\right]$$  \hspace{1cm} (6)

When the PV cells is open circuit $(I=0)$, we can get that $V=V_{oc}$. The equation (7) can be obtained by putting $V=V_{oc}$ into the equation (6).

$$\lambda = \frac{1}{V_{oc}} \ln\left(\frac{I_{sc}}{I_0}\right)$$  \hspace{1cm} (7)

The equation (8) can be obtained by putting the equation (7) into the equation (6).

$$I = I_0 \left[1 - \left(\frac{I_0}{I_{sc}}\right) \exp\left(-\frac{1}{V_{oc}} \ln\left(\frac{I_{sc}}{I_0}\right) (V + IR_s)\right)\right]$$  \hspace{1cm} (8)

We can obtain the conditions that $I=I_m$ and $V=V_m$ at the maximum power point. The equation (9) can be obtained by putting the above conditions into the equation (8) and simplifying it.

$$R_s = \left[\frac{V_{oc}}{\ln\left(\frac{I_{sc}}{I_0}\right)} - \frac{V_m}{I_m}\right] / I_m$$  \hspace{1cm} (9)

Because $I_0$ is related to the nature of the solar cells’ materials, it reflects the maximum composite ability of photon-generated which comes from the solar cells. It is generally considered that it is approximately a constant and not affected by the light intensity. Under standard testing conditions, $I_0/I_{sc} \approx 10^{-10} \sim 10^{-8}$. In order to simplify the analysis, usually $I_0/I_{sc} \approx 10^{-9}$ is adopted. As is shown in equation (9), based on the four technical parameters ($I_{sc}$, $V_{oc}$, $I_m$, $V_m$) of PV module under the corresponding standard test condition which are provided by the manufacturer, it is easy to calculate the value of series resistance under the corresponding standard test condition. By putting the known data ($V_{oc} = 37.64V$, $I_{sc} = 8.41A$, $V_m = 30.87V$, $I_m = 8.1A$) of PV module into the equation (9), we can obtain that $R_s = 0.0957 \Omega$ under standard test conditions. So taking $R_s = 0.1\Omega$ as the value of the series resistance of PV module without aging fault under standard test condition. Under standard test conditions, the FF of module without fault is generally between 0.7 and 0.75. Therefore, it can be judged that when the fill factor FF is less than 0.7, aging fault has occurred. When the value of fill factor (FF) is below 0.6, it can determine that serious aging fault has occurred. In addition, the fill factor (FF) of PV module is affected by the irradiation and temperature. The value of the fill factor changes with irradiation, as shown in figure 7.
The fill factor is also related to the temperature of the solar cell. And the curve of current-voltage relationships will soften up because the leakage current of p-n junction increase with the temperature. And it makes FF generally decreases with the increase of temperature.

Calculating the fill factor (FF) by considering the factors of the irradiation and temperature. When the value of FF is less than 0.7, it can be judged that the module is in a failed state of aging. According to the fill factor FF at this time, the degree of aging fault can be obtained. Further, the remaining useful life can be calculated based on the using time of the module, so that the failure module can be replaced in time. Assuming that the module has been used for N years, the fill factor calculated at this time is FF. When the value of FF is between 0.6 and 0.7, the annual deterioration rate (x) of PV module can be calculated by equation (10).

\[
x = \frac{0.7 - FF}{(0.7 - 0.6) \times N} \times 100\%
\]  

Equation (10)

The remaining useful life of PV module can be calculated by equation (11).

\[
M = \frac{1}{x} - N
\]  

Equation (11)

3.4 Steps of fault diagnosis

The on-line fault diagnosis proposed in this paper can be roughly divided into the following steps: (1) Comparing the simulated output power with the measured output power, if the output power loss rate exceeds 15%, it can be judged that an abnormal power loss has occurred; (2) Taking into account the irradiation of several measurement points where the abnormal power loss occurred, if the irradiation drops suddenly, it can be judged that the power loss comes from the shadow, elsewise it comes from the faults; (3) Using the open circuit voltage of the module to determine whether the short circuit fault has occurred and roughly estimate the number of cells which are short-circuited; (4) Calculating the fill factor (FF) based on the condition of irradiation and temperature. It can determine whether the aging fault has occurred and obtain the degree of the aging fault based on the value of FF. The basic process of fault diagnosis is shown in figure 8.
When the short circuit fault happens, calculate the number of cells which are short-circuited based on the open circuit voltage. When the state of the module is judged to be between normal and severe aging, the remaining useful life of the module can be calculated roughly based on the annual aging rate.

4. Simulation and experimental validation

In order to verify the validity and accuracy of the fault diagnosis method proposed in this paper, the simulation and experiment are carried out. The parameters of simulation model come from the PV module which models for JHX250P60. Parameters under standard test conditions are shown in table 2.

Table 2. Parameters of experimental module.

| Parameters                          | values   |
|-------------------------------------|----------|
| Rated power (Wp)                    | 250W     |
| Open circuit voltage (Voc)          | 37.64V   |
| Short-circuit current (Isc)         | 8.41A    |
| Voltage of Maximum power point (Vm) | 30.87V   |
| Current of maximum power point (Im) | 8.10A    |

The model of micro inverter used in the experiment is ANI-250, which has the functions of DC-DC and the maximum power point tracking (MPPT). The micro inverter can record the maximum output power of the module at different times and sample the working voltage and the working current of the module at the same time. The open circuit voltage, the short circuit current, the voltage of maximum power point and the current of maximum power point are scanned and sampled every 10 minutes. The micro inverter has a built-in communications module which uploads the data to the server terminal in
real time.

In order to verify the fault diagnosis method, the experiment should be carried out under the conditions of normal working, different shadow ratio, different degree of short circuit fault and different degree of aging fault. Considering the effects of irradiation and temperature on the fault diagnosis results, the 7 different time-points of the day were randomly selected. The module works properly at point A. Three cells of PV module are covered by the shadow at point B. At point C, twelve cells of PV module are covered by the shadow. At point D, 6 cells of the module are short-circuited. At point E, 9 cells of the module are short-circuited. At point F, the module is in series with a resistance of 0.5 ohm. At point G, the module is in series with a resistance of 1.1 ohm.

| Measurement points | Simulated power | Measured power | Power loss rate(k) | Sudden decline of irradiation |
|--------------------|----------------|----------------|-------------------|-----------------------------|
| A                  | 122.75         | 105.79         | 13.8%             | None                        |
| B                  | 140.90         | 78.55          | 44.3%             | Yes                         |
| C                  | 173.66         | 1.18           | 99.9%             | Yes                         |
| D                  | 223.72         | 175.84         | 21.4%             | None                        |
| E                  | 197.26         | 130.78         | 33.7%             | None                        |
| F                  | 171.01         | 143.31         | 16.2%             | None                        |
| G                  | 155.36         | 119.32         | 23.2%             | None                        |

By comparing the simulated power with the measured power of each measurement point, it can be obtained that abnormal power loss occurred at all time-points except point A. Combined with the situation of sudden decline of irradiation, it can be concluded that partial shadow occurred at point B and point C. And it can be initially judged as short circuit or aging fault occurred at point D, E, F and G.

Further, the characteristic parameters of PV module at point D, E, F and G are shown in table 4 and table 5.

| Measurement points | $V_{oc}$ | $V'_{oc}$ | $\alpha$ |
|--------------------|---------|----------|---------|
| D                  | 34.78   | 31.63    | 6.3     |
| E                  | 33.66   | 28.74    | 9.84    |

| Measurement points | $I_{sc}$ | $V_{oc}$ | $P_m$ | FF |
|--------------------|----------|----------|-------|----|
| F                  | 5.87     | 37.14    | 143.31| 0.66|
| G                  | 5.46     | 36.85    | 119.32| 0.59|
By comparing the open circuit voltage of the module, it can be judged that the short circuit fault has occurred at point D and point E. And the open circuit voltage is used to estimate the number of short circuited cells roughly. Diagnostic results are shown in table 6. It can be judged that aging fault has occurred at measurement point F, G by calculating the value of FF. The remaining useful life of PV module can be roughly calculated based on the years that the module had been used for and the value of FF. The PV modules used in the experiment have been used for 3 years, namely N=3. Diagnostic results are shown in table 7.

| Measurement points | Fault type     | The number of short circuit cells |
|--------------------|---------------|----------------------------------|
| D                  | Short circuit | 6                                |
| E                  | Short circuit | 9                                |

Table 7. Diagnosis of time-point F and G.

| Measurement points | Fault type     | Remaining useful life |
|--------------------|---------------|-----------------------|
| F                  | Little aging  | 4.5                   |
| G                  | Serious aging | /                     |

The experimental results show that the proposed method is effective and accurate. By using this method, we can make full use of real-time capability of the method based on power comparison and the accuracy of the diagnosis based on characteristic parameters. Experimental results show that the accuracy of this method is more than 90%. For erroneous judgments the possible reasons are as follows:

The measured data is limited by the precision of the sensor and the acquisition device, which leads to the errors between the input data of simulation model and the experimental data;

The maximum power point tracking of the PV module used in the experiment cannot track the maximum power point accurately, which leads to the error in the calculation of FF;

A variety of faults could occur at the same time during the working of PV module. The method proposed in this paper only uses a single criterion to diagnose a class of faults, which may result in a false diagnosis.

Compared with existing methods in literature, the method proposed in this paper has made the following improvements. First, compared with infrared picture analysis, this diagnosis result is not affect by the surrounding environment. Second, this method can detect three different types of faults. Finally, this method is more accurate and can reach more than 90%.

5. Conclusions

A real-time on-line fault diagnosis method based on power loss and the I-V output characteristics has
been presented. We drew the following conclusion:

- Based on the comparison of the simulated power with the measured power of PV module, the power loss rate ($K$) can be obtained. By analyzing the value of $K$, it can be known whether abnormal power loss has occurred.
- If $K$ is greater than 15% and the irradiation of the module is normal, it can determine whether short circuit has occurred by comparing the measured open circuit voltage and the simulated open circuit voltage.
- When a module has short circuit fault, the number of short circuited cells can be calculated on the basis of the open circuit voltage.
- The value of $FF$ will decrease when aging fault occurs. If $K$ is less than 0.7, it can be judged that the aging fault has occurred.
- When a module is short circuit, the degree of aging can be obtained by calculating the value of $FF$. Then the remaining useful life of PV module can be roughly estimated based on the years the module had been used for.

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