Analysis and diagnosis of hot spot failure in c-Si PV module

Yun Ping\(^1\),*\(^1\), Liu Yuzheng\(^1\), Liu Heng\(^2\) and Zhang Zhixiang\(^2\)

\(^1\)Sungrow Power Supply Co., Ltd., Hefei, Anhui, 230088, China
\(^2\)The College of Electrical and Automated Engineering, Hefei University of Technology, Hefei, Anhui, 230030, China

*Corresponding author’s e-mail: yunping@sungrowpower.com

Abstract. The hot spot types in crystalline silicon photovoltaic(c-Si PV) module can be divided into the followings: series resistance type, cell reverse biased type, bypass diode over-current type and direct-current (DC) arc type. The most common type was cell reverse biased type (hot spot as we know). By collecting all kinds of failed PV module (PID, aging, glass fragmentation, short circuit of bypass diode, and back sheet cracking) in practical power station, the characteristic parameter of cell reverse biased hot spot was determined after comparative analysis of IV curve. Based on this characteristic parameter, a set of diagnostic procedure was designed. Then we tested the procedure on the power optimizer, the diagnostic accuracy of hot spot was 95% and the recall rate was 96%. In order to reduce the temperature of hot spot, we added aluminum fins on the back of PV module, and the temperature of hot spot was lowered maximum by 19.3°C compared with conventional module, which indicated that the aluminium fins have a certain cooling effect.

1. Introduction

C-Si PV module is a kind of energy conversion device, which mainly converts light energy to electric energy and thermal energy. In the process of outdoor using, it can be affected by various environmental factors and system configuration, such as ultraviolet ray, high temperature, high humidity, shielding, snow, high voltage of module to the ground, etc., which may lead to degradation or failure[1]. According to the literature and a large number of the failure feedback of module manufacture, the main types of failures are hot spot (the cell reverse biased type, the direct-current (DC) arc type, the bypass diode over-current type), PID (Potential Induced Degradation), discoloration (EVA and back sheet yellowing, snail), LeTID (Light and elevated Temperature Induced Degradation) [2, 3, 4, 5, 6]. These failures lead to the reduction of photoelectric conversion efficiency, such as PID leads to the reduction of electric potential because of PN junction’s polarization. Hot spots cause more energy to convert to heat, and less light to generate electricity. In order to improve the power generation of PV station, on the one hand, it is necessity to improve the quality and reduce degradation of PV module through continuously technological innovation [4]. On the other hand, in practical power station, failed module should be found timely through detection technology for maintenance or replacement, which can also improve the power generation of the system effectively.

In this paper, based on all kinds of failed modules collected in the power station, the characteristic parameter of cell reverse biased hot spot was extracted, and a set of diagnostic procedure based on IV curve was given, which was tested and verified on the power optimizer. And more detail fault detection researches about IV curves could be seen in the references of [7, 8].
2. Hot spot analysis of c-Si PV modules

The heating of c-Si PV modules is mainly divided into two parts: the normal part of light heat energy, and the abnormal heat of hot spot. And the normal light heat energy is the thermal energy produced in the process of photoelectric. Abnormal heat mainly includes the following types: series resistance type, cell reverse biased type, bypass diode over-current type and DC arc type. Fig. 1 showed a hot spot case of series resistance type, the bus-bar welding place had a significantly high temperature (maximum temperature: 112°C), and faulty soldered joint might lead to the increase of series resistance, which induced the hot spot. Fig. 2 showed a hot spot case of cell reverse biased type. When photoelectric of a cell in module was smaller than the working current of module, voltage of the cell was reversed, and the leakage current flowed through the parallel resistance to generate hot spot. There were two hot spot cells in IR (Infrared thermal Imaging, equipment model: FILR T420), and EVA on the front of hot spot cell showed a significant discoloration. Fig. 3 showed a hot spot case of bypass diode overcurrent type, the maximum temperature of Junction box (J-box) reached 266°C in IR, and J-box was melted with package failure. When the current flowing through bypass diode was larger than the rated current, hot spot was formed.

Fig. 4 showed a hot spot case of DC arc type. When there was an insulating medium between the positive and negative electrodes, the positive and negative charges would gather on opposite sides of the insulating layer, and discharge would occur when certain conditions were met, it usually accompanied with high temperature heat. In the case of Fig. 4, the lapped length of interconnected welding strip was too short, and the residual EVA was not removed completely in the process of cell repairing. There was an insulating layer between lapped welding strips, which met the condition of DC arc leading to high temperature and firing the module.
After the IR test of 100MW power stations, very few series resistance type of hot spot module was found. And most of the others were cell reverse biased hot spot modules. The bypass diode over-current hot spot and DC arc hot spot only appeared in the customer’s complaint cases of some module manufacturer, the actual proportion was smaller. In this paper, the most common type of cell reverse biased hot spot in power stations was analysed, and the characteristic parameter was extracted by IV test (equipment model: AV6591) comparison. Using this characteristic parameter, a set of hot spot diagnostic procedure, based on IV curves, was established. After testing in power optimizer (get the IV curves), the accuracy rate was 95%, and recall rate was 96%, which showed a higher application value.

3. Hot spots test and diagnosis

3.1. Extraction of characteristic parameter

Based on the principle of cell reverse biased hot spot module, and a large number of sample tests by IV and IR, also compared with other failures (PID, aging, glass fragmentation, back sheet cracking, bypass diodes short circuit), we found two different kinds of IV curves for hot spot modules, here we defined as step-type hot spot and non-step-type hot spot. Fig. 5 showed current-voltage (IV) curves’ comparison among normal module and several kinds of failure modules, such as back sheet cracking, aging, PID, bypass diode short circuit. They all showed smooth IV curves without step characteristics, but changing in open circuit voltage $V_{oc}$, short circuit current $I_{sc}$, and filling factor $FF$ etc.

Fig. 6 showed the IV curves’ comparison among two types of hot spot modules and normal module, as well as the glass fragmentation. It can be seen that the characteristic parameter of cell reverse biased hot spot module was the linearity of IV curve in the left of local maximum power point closest to $V_{oc}$, which can be used for the diagnosis of hot spot.

In the process of failure diagnosis based on the IV curve, the two different IV curves of hot spots should be analysed carefully. The IV curve of non-step-type hot spot module had great similarity with aging module and normal module. The IV curve of step-type hot spot module had great similarity with glass fragmentation.

Fig. 7 showed the IV and voltage-power (VP) curves of non-step-type hot spot module. The point corresponding to the local maximum power point closest to $V_{oc}$ on the IV curve was point B, and point A was in the left of point B with 5 data points’ interval, we diagnosed the non-step-type hot-spot by detecting the linearity of the AB curve. Using the point A and point B to establish a linear equation \(y = kx + b\) (as shown in Fig. 7: Magnify of A-B interval), and calculated the distance between IV curve and the linear equation, defined as $d_i$, and then summed them up, defined as $SUM d_i$, we used $SUM d_i$ to test curve linearity.

\[
y = kx + b
\]  

Fig. 8 showed the IV and VP curves of step-type hot spot module. We used the features of concave and convex function to determine the step interval AB in IV curve. We diagnosed the step-type hot-spot by detecting the linearity of the AB curve. Using the point A and point B to establish a linear equation \(y = kx + b\) (as shown in Fig. 8: Magnify of A-B interval), and calculated the distance between IV curve and the linear equation, defined as $d_i$, then calculated the average of them, defined as $AVG d_i$, we used $AVG d_i$ to test curve linearity.
Figure 5. Comparison of IV curves between different failure types and normal PV module.

Figure 6. Comparison of IV curves among hot spot, glass fragmentation and normal PV module.

Figure 7. IV and VP curves of non-step-type hot spot module.

Figure 8. IV and VP curves of step-type hot spot module.

Table 1 showed the statistics of failures and normal c-Si PV modules which were collected in power stations. It contained 39.67% of hot spot modules. The IV curves gotten from the above modules were used as training samples to obtain the threshold of hot spot module with SUM $d_i = 0.03$ and AVG $d_i = 0.01$, which would be used in the diagnostic procedure.

| Failure Type          | Number $N$ | Proportion (%) |
|-----------------------|------------|----------------|
| Hot spot              | 407        | 39.67          |
| PID                   | 27         | 2.63           |
| Aging                 | 105        | 10.23          |
| Glass fragmentation   | 31         | 3.02           |
| Back sheet cracking   | 150        | 14.62          |
| Bypass diodes short circuit | 46       | 4.48           |
| Normal module         | 260        | 25.34          |

3.2. Diagnosis of hot spot

Fig. 9 showed the flow chart of diagnosis for hot spot module, which was described briefly as follows:

Firstly, we got the IV curves from power optimizer (Sungrow Power: SP750).

Secondly, we determined the number of local maximum power points, defined as $N$. 
When $N > 1$, it was step-type hot spot, we used the linearity of step interval in IV curve and the power (defined as $P_s$) of hot spot cell to judge the hot spot. It was hot spot when $\text{AVG } d_i \leq 0.01$ and $P_s \geq 50W$, otherwise, it was not hot spot.

When $N \leq 1$, it was non-step-type hot spot, we used the linearity of AB curve and the power of hot spot cell to judge the hot spot. It was hot spot when $\text{SUM } d_i \leq 0.03$, and $P_s \geq 50W$, otherwise, it was not hot spot; The $P_s$ of hot spot cell can be calculated by acquiring irradiance $G$, module information, IV curve information and module working current $I_m$.

![IV test diagram](image)

**Figure 9. Flow chart of diagnosis for hot spot module.**

According to the flow chart of Fig. 9, we completed the diagnostic procedure in Java format. And then we tested this procedure in 30 PV strings with power optimizer (Fig. 10 showed one PV string photo), which contained 626 PV modules with 180 failures and hot spot modules. The diagnostic results showed that the diagnostic accuracy of hot spot was 95% and the recall rate was 96%, which showed certain application value.

![PV string and power optimizer](image)

**Figure 10. The PV string (a) and Sungrow’s power optimizer (b).**

### 4. Cooling of hot spot module

In order to reduce the hot spot temperature, we added aluminum fins (thickness: 0.3mm, height: 20mm, spacing: 20mm) on the back of module by specific lamination technology. Fig. 11 showed back view of cooling module with aluminum fins. By setting the same shielding to simulate hot spot on cooling module and normal module, the temperature of hot spot cell in both cases was tested. As shown in Fig. 12, the 75% area of a cell in module was shielded at 11:01. After 10 minutes, the temperature of hot spot was basically stable. In stable period of 11:11 and 11:33, the average temperature deviation was $16.8^\circ C$, and the maximum temperature deviation was $19.3^\circ C$. It showed that aluminum fins had a certain effect on cooling the temperature of hot spot.
5. Conclusions

This paper analysed the hot spots of c-Si PV modules, which included the following types, such as series resistance type, cell reverse biased type, bypass diode over-current type, and DC arc type. In the practical power station, the most common hot spot modules of cell reverse biased type were tested by IR and IV, which had two different kinds of IV curves. After extracting of characteristic parameter of hot spot module, a set of diagnostic procedure was completed in Java format. As tested by the power optimizer, the diagnostic accuracy of hot spot was 95% and the recall rate was 96%. In order to reduce the temperature of hot spot, aluminum fins were added on the back of the module, and the temperature of hot spot was lowered maximum by 19.3°C compared with conventional module, which indicated that aluminum fins have obvious cooling effect.

References

[1] Claudio F and Daniel P. (2012) Why Do PV Modules Fail? Energy Procedia, R-15:379-387.
[2] Sergiu V, Dezso S, Peter H, et al. (2016) Fault identification in crystalline silicon PV modules by complementary analysis of the light and dark current-voltage characteristics. Prog. Photovolt: Res. Appl., R-24:517-532.
[3] Marc K, Sarah K, Corinne P, et al. (2014) Review of Failures of Photovoltaic Modules. In: IEA PVPS Task 13, External final report IEA-PVPS.pp.
[4] Eric J, R. Paul, Narendra S, et al. (2016) Manufacturing metrology for c-Si module reliability and durability Part III: Module manufacturing. Renewable and Sustainable Energy Reviews, R-59:992-1016.
[5] Dirk C, Timothy J, John H, et al. (2017) Photovoltaic failure and degradation modes. Prog. Photovolt: Res. Appl., R-25:318-326.
[6] Shifeng D, Zhen Z, Chenhui, et al. (2017) Research on hot spot risk for high-efficiency solar module. Energy Procedia, R-130:77-86.
[7] Sergiu S, Dezso S, Tamas K, et al. (2015) Diagnostic method for photovoltaic systems based on light I-V measurements. Solar Energy, R-119:29-44.
[8] M. Bressan, Y. El Basri, A.G. Galeano, et al. (2016) A shadow fault detection method based on the standard error analysis of I-V curves. Renewable Energy, R-99:1181-1190.