Microelectronics Reliability 138 (2022) 114705

Contents lists available at ScienceDirect

Microelectronics Reliability

journal homepage: www.elsevier.com/locate/microrel

A data-driven photovoltaic string current mismatch fault diagnosis method based on I-V curve

Zhixiang Zhang [a], Mingyao Ma [a,*], Wenting Ma [a], Rui Zhang [b], Jun Wang [b]

[a] National and Local Joint Engineering Laboratory for Renewable Energy Access to Grid Technology, Hefei University of Technology, Hefei, China
[b] Sungrow Power Supply Co., Ltd., 1688 Xiyou Street, Hefei 230088, China

ARTICLE INFO

Keywords:
PV string
Current mismatch
Data driven
I-V curve
Fault diagnosis

ABSTRACT

Due to the complex operating environment, current mismatch faults often occur in photovoltaic (PV) strings in the actual PV plants, which seriously reduces the power of the entire string. This paper investigates and collects the data of mismatched PV strings in an actual PV plant, and further the fault characteristics of mismatched PV strings are extracted through the I-V curve. A data-driven online diagnosis method for current mismatch faults based on string I-V data is proposed. The method uses the I-V data to construct a detection line, and the inflection point and step features on the I-V curve caused by current mismatch can be detected simply and quickly through the parallel movement of the detection line and the positional relationship between the line and the I-V data. The experimental verifications from the actual PV plant are demonstrated to show the effectiveness of the proposed method for PV string current mismatch fault.

1. Introduction

With the rapid development of the PV industry, its reliability has also received more and more attention. In practice, PV strings are often affected by shadows, hot spots, etc., which will cause current mismatch in the strings [1]. As a common and serious fault type in PV strings, current mismatch will not only affect the energy yield of the entire system, but even cause safety hazards. Therefore, it is necessary to carry out accurate diagnosis of PV strings and provide suggestions for operation and maintenance personnel, and timely troubleshooting has a significant effect on improving the reliability of PV systems and increasing economic benefits.

Existing PV system fault diagnosis methods can be roughly divided into: electrical measurement, model-based, infrared image analysis and data-driven methods [2]. The electrical measurement method is to measure the operating parameters of the PV string, and to detect faults by comparing and analyzing the operating status, which may require a large number of sensors and increase the cost of the system [3]. The model-based methods diagnose faults by comparing the output of the model with the actual measurements [4]. However, the modeling process is complex and the diagnostic results depend on the model accuracy. The infrared image analysis method can quickly locate faults by comparing temperature differences between PV modules, but this method requires expensive infrared equipment [5]. The data-driven method can accurately diagnose the fault of the PV system by obtaining the effective data and then analyzing it, and this process does not require additional hardware equipment, which is the most promising fault diagnosis method at present [6].

Because the I-V curve represents all possible operating points of a PV cell, module or string, it can well characterize the fault of the PV module or string. As the standard IEC62446 states, the shape of the I-V curve provides information about faults, including damaged cells, short-circuit bypass diodes, partial shading, mismatch, reduced shunt resistance and increased series resistance [7]. The standard IEC62446-1 divides the failure of the I-V curve into six shapes, and the step is one of them, which indicates the current mismatch fault. In this paper, through the data collection of the PV strings with current mismatch in the actual PV power plant, the fault characteristics of the current mismatch strings are extracted, and a data-driven fault diagnosis method based on the I-V curve of PV strings is proposed. Compared with other methods, this method requires no additional equipment and is machine-friendly to quickly detect current mismatch faults in PV strings online. Most data-driven based methods separate faults from operating data through intelligent classification algorithms, such as random forests, artificial neural networks, decision trees, etc. [8–10]. These methods are relatively low-cost and have good real-time performance, but they rely on

* Corresponding author.
E-mail address: miyama@hfut.edu.cn (M. Ma).

https://doi.org/10.1016/j.microrel.2022.114705
Received 25 May 2022; Received in revised form 12 July 2022; Accepted 1 August 2022
Available online 25 September 2022

expertise knowledge and require large amounts of training data. However, the method in this paper does not require data training and complex classification algorithms. The method proposed in this paper can simply and quickly detect the inflection point and step features on the I-V curve caused by current mismatch through the parallel movement of the constructed detection line and the positional relationship between the detection line and the I-V data, which has high computational efficiency and low complexity. Combined with the string inverters with the I-V scanning function, the I-V curve of each PV string can be quickly obtained and the current mismatch fault of the PV string can be diagnosed online, which shows that the method has strong adaptability and high practical application value.

2. Data collection and characteristic analysis

2.1. Characteristics of PV strings

In order to increase the output voltage of a grid-connected PV system, many PV modules are usually connected in series to form a PV string. One PV string or multiple PV strings are connected in parallel to one maximum power point tracking (MPPT) of the string inverter. The simplified connection diagram of the PV power generation system is shown in Fig. 1.

Due to the series relationship between PV modules, the output voltage of the PV string is the sum of the voltages of each PV module, and the current of the PV string is equal to the current flowing through each PV module. Therefore, the output of a PV string is the superposition of each module in the string. In theory, the I-V curve of a PV string is formed by the composite superposition of the I-V curves of each module in the string. Under normal conditions, the I-V curves of PV string and modules are shown in Fig. 2.

As an important function of inverters, MPPT has been widely studied. The realization of MPPT technology requires the inverter to sample the output voltage and current parameters of PV strings, and search from the open-circuit voltage point to the direction of the maximum power point (MPP) [11]. If the voltage and current range of the MPPT search is further expanded, that is, the voltage and current data of the PV string are collected from the open-circuit voltage point to the short-circuit current point, then the I-V curve of the PV string can be obtained [12]. This process does not require additional hardware equipment and does not increase the cost of the system. The schematic diagram of MPPT technology and I-V scanning technology is shown in Fig. 3. Both MPPT and I-V scanning collect the output voltage and current data of PV strings, but the difference is that the collected voltage ranges are different. The I-V scanning collects the output voltage and current data of the PV string from the open-circuit voltage point to the short-circuit current point, while the MPPT technology searches from the open-circuit voltage point to the MPPT. Therefore, the I-V scanning technology of string inverters is more and more used to obtain the I-V curves of PV strings.

2.2. Data collection of faulty PV strings

Collecting faulty PV string data from the installed PV plant is a

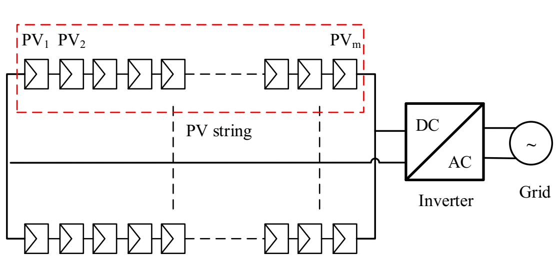

Fig. 1. The simplified basic structure of PV system.

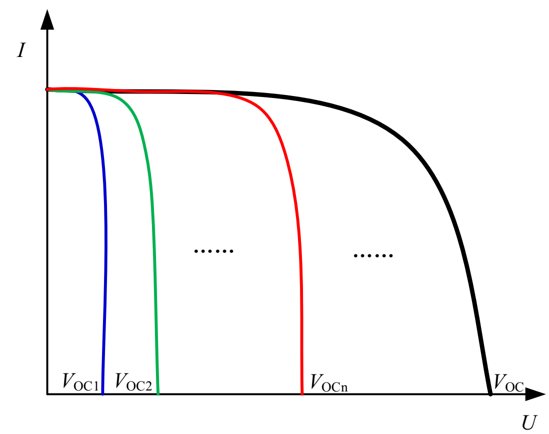

Fig. 2. Schematic diagram of the composition of the I-V curve of a PV string under normal conditions.

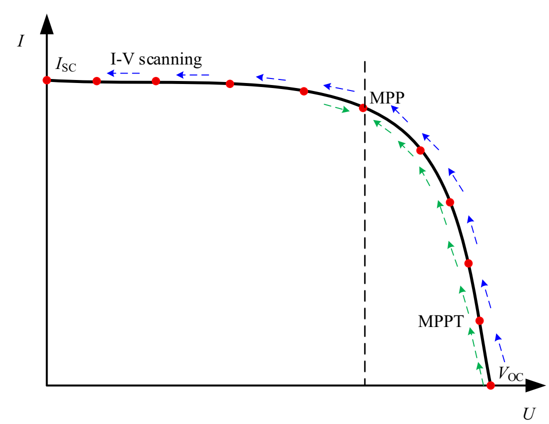

Fig. 3. Schematic diagram of MPPT and I-V scanning.

challenging task. The data of faulty PV strings are collected by means of infrared camera, manual observation and simulation. A total of >500 PV strings with current mismatch faults were collected, from a 120 MW PV plant in Lingbi County, Anhui Province, China (33°32′N 117°33′E), which has been in operation for three years. The power station is a distributed PV power plant on a flat ground. A PV string in the distributed PV system includes 22 PV modules connected in series which are connected to the 1000 V DC system. The PV modules in the string are constituted of three 20-cell substrings connected in series. Each substring is connected in parallel to a bypass diode, which can bypass the current of a severely damaged string. The nameplate parameters of the PV modules are shown in Table 1.

2.3. Analysis of fault characteristics

Current mismatch is the most common type of fault in PV strings. The operating environment of PV power plants is complex, and actual PV power plants are often shaded by trees, weeds, dirt, etc. during operation

Table 1
PV module nameplate parameters.

Parameters	Value
Open circuit voltage V_{OC}	38.4 V
Short circuit current I_{SC}	9.64 A
Current at the maximum power point I_m	9.06 A
Voltage at the maximum power point V_m	31.4 V
Peak power P_m	285 W

[13]. When the PV modules in the PV string are shaded, the output current of the shaded modules will drop. Due to the series relationship between the modules, the PV string will have current mismatch at this time, and the I-V curve of the PV string will have an inflection point and step features. In order to study the influence of different mismatch degrees on the I-V characteristics of PV strings, the I-V curves of PV strings are obtained through the I-V scanning function of the string inverter in sunny weather, and the I-V curves of PV strings with different degrees of mismatch are shown in Fig. 4. It can be concluded that the current mismatch makes the I-V curve of the PV string appear inflection points and steps, and the concave and convexity of the I-V curve changes. With the increase of the degree of shading, the current in the step decreases, and with the increase in the number of modules shading, the length of the step increases.

3. Fault diagnosis process

3.1. Data acquisition and preprocessing

The I-V data used for fault diagnosis in this study were obtained from string inverters. The I-V scanning function of the inverter can obtain the I-V data of PV strings under one MPPT within 700 ms. Each string I-V data contains 128 sets of voltage and current data points with different voltages, which are recorded as (U_i, I_i) in the descending order of voltage, where $i = 0, 1, 2, \ldots, 127$. Because the scanning time is very short, changes in irradiance during the scanning can be ignored. However, due to data acquisition problems, data jitter may be relatively large, which affects the subsequent diagnosis. Theoretically, the current of the I-V data decreases as the voltage increases. Therefore, in order to eliminate the outliers, the raw I-V data is preprocessed. The voltage data corresponding to the PV string I-V data remains unchanged, for current data I_i satisfies the following conditions (Eq. (1)).

$$\begin{cases} I_i > I_{i-1} \\ I_i > I_{i+1} \end{cases} \tag{1}$$

or meet the following conditions (Eq. (2)).

$$\begin{cases} I_i < I_{i-1} \\ I_i < I_{i+1} \end{cases} \tag{2}$$

The current value is then interpolated to satisfy the following equation.

$$I_i = \frac{I_{i-1}(U_i - U_{i+1}) + I_{i+1}(U_{i-1} - U_i)}{U_{i-1} - U_{i+1}} \tag{3}$$

After the above process, the preprocessed data (U_i, I_i) is obtained. A set of raw I-V data and preprocessed data are compared in Fig. 5. It can be seen that after processing, the abnormal data on the raw I-V curve can be well eliminated.

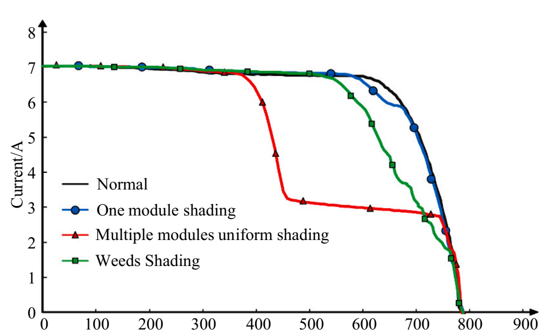

Fig. 4. I-V curves of PV strings under different mismatch degrees.

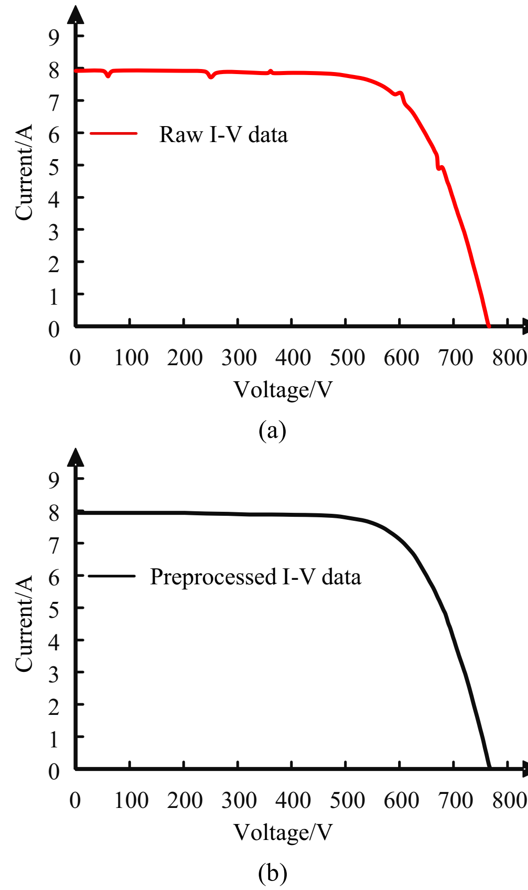

Fig. 5. Comparison before and after I-V data preprocessing. (a) Raw I-V data. (b) Preprocessed I-V data.

3.2. Current mismatch diagnosis

According to the I-V characteristics of the mismatched strings, the mismatch causes the I-V curve to have steps and inflection points, and the concave and convexity of the I-V curve changes. In this paper, a method of constructing a detection line using I-V data is proposed to detect the mismatch of PV strings. The mismatch detection method is shown in Fig. 6. The detection line is constructed with the slope of the short-circuit current point (U_{127}, I_{127}) and the open-circuit voltage point (U_0, I_0) on the I-V curve, and multiple groups of parallel line clusters are obtained by changing the intercept. The expressions for the slope and the equation of the straight line are as follows.

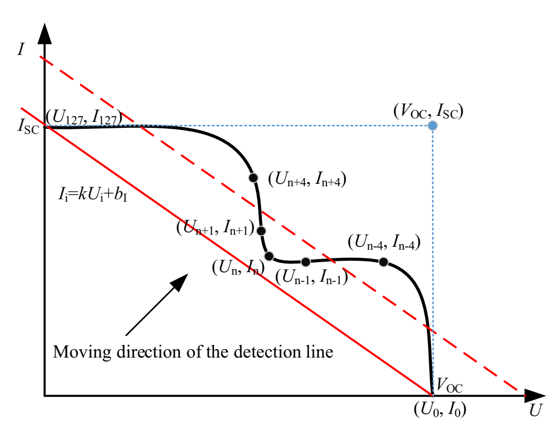

Fig. 6. Schematic diagram of the current mismatch fault detection method.

$$k = \frac{I_{127} - I_0}{U_{127} - U_0} = -\frac{I_{127}}{U_0} \tag{4}$$

$$I_i = kU_i + b_I \tag{5}$$

where b_I is the variable intercept of the detection line, and it is also the intersection of the detection line and the current axis. The initial value of b_I is the short-circuit current I_{127}. In order to ensure that the detection line envelopes the entire I-V curve, theoretically, the maximum value of b_I will not exceed twice the short-circuit current value, that is, $2I_{127}$. Because when the detection line passes through the point (U_0, I_{127}), the I-V curve is completely below the detection line, and the intercept b_I value at this time can be obtained as $2I_{127}$, so the range of b_I is [I_{127}, $2I_{127}$].

Different step sizes b_I represent different detection lines, and the step size increment Δb threshold is set to 0.02. Compare the data points on the I-V curve with each detection line, if both of the following conditions are met:

(i) There is a point (U_n, I_n) on the curve below the detection line, that is, $I_n < kU_n + b_I$;
(ii) The two points adjacent to this point are also located below the line, namely $I_{n\text{-}1} < kU_{n\text{-}1} + b_I$, $I_{n+1} < kU_{n+1} + bI$, $I_{n\text{-}1} > 0$;
(iii) The other two points adjacent to this point are located above the line, namely $I_{n\text{-}4} > kU_{i\text{-}4} + b_I$, $I_{n+4} > kU_{n+4} + b_I$, $I_{n\text{-}4} > 0$.

Then the I-V curve has an inflection point, stop the comparison, and the PV string has a current mismatch. If it is not satisfied, change the value of b_I, let $b_I = b_I + \Delta b$, compare with the next detection line, repeat the above judgment, until the upper limit of b_I, if the above conditions are still not satisfied, then there is no mismatch. As shown in Fig. 7, the mismatch detection result of a PV string that is irregularly shaded by weeds. At this time, the point on the I-V curve that satisfies the above conditions can be found by the detection line, and there is a mismatch in the string.

3.3. Algorithm

For the acquired PV string I-V data, the preprocessing is performed to obtain relatively smooth I-V data, and then the current mismatch fault is detected according to the above detection method. The specific diagnosis process is shown in Fig. 8.

4. Validation and discussion

The data used in the experimental verification in this paper are all derived from the PV strings in the distributed PV system. Through the I-V scanning function of the string inverter connected to the PV strings, the I-V curve data of each string connected to the inverter can be easily and quickly obtained online, and then the mismatch fault diagnosis can be performed on the I-V data of each string. The structure of the system is shown in Fig. 9. After the fault diagnosis is performed, if there is a fault, it will be reported to the monitoring center to provide an alarm to the operation and maintenance personnel. The online diagnosis technology can greatly reduce the cost of manual operation and maintenance and avoid the serious consequences that may arise from PV string mismatch fault.

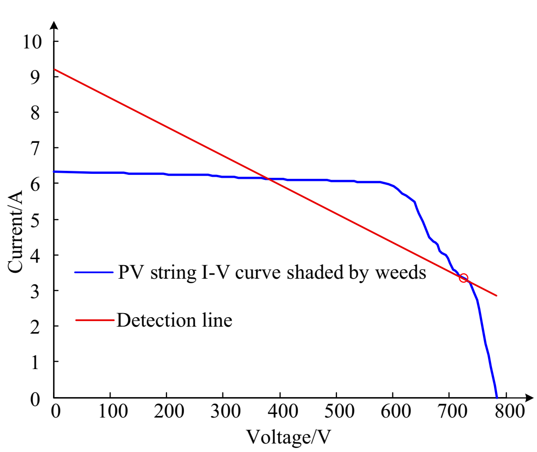

Fig. 7. Diagnostic results of the PV string shaded by weeds.

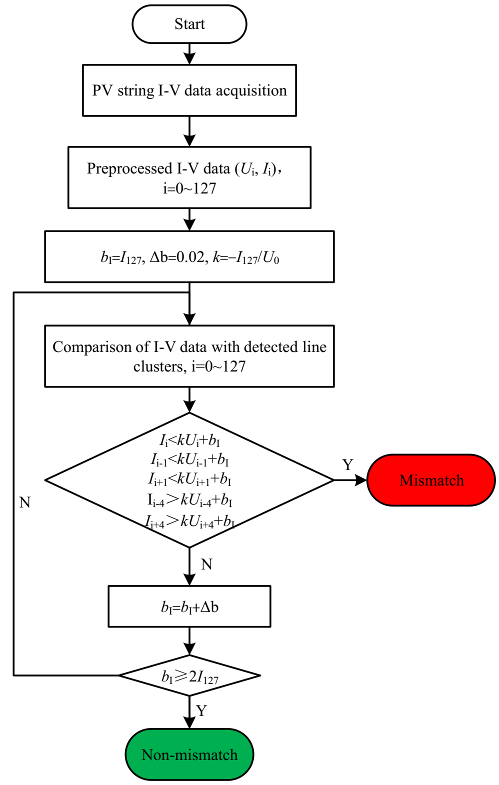

Fig. 8. Flow chart of current mismatch fault diagnosis.

Combined with the characteristics of the I-V scanning of the string inverter, the I-V data of the PV string is obtained by issuing the I-V scanning command, and the current mismatch fault in the string is identified according to the above diagnosis algorithm. In order to further verify the accuracy of the method and the sensitivity to non-obvious current mismatch fault detection, we simulated and verified the case of a single module shading in the string. As shown in Fig. 10(a), one PV module in the string is shaded. For the setting of partial shading in the experiment, the cardboard with light transmittance of 0 was used to partially shade the PV module. The results are verified, as shown in Fig. 10(b). At this time, the fault characteristics in the I-V curve are not obvious, and the method can still detect the distortion of the I-V curve caused by the current mismatch.

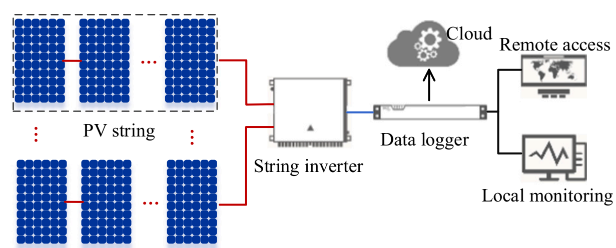

Fig. 9. Schematic diagram of fault diagnosis system.

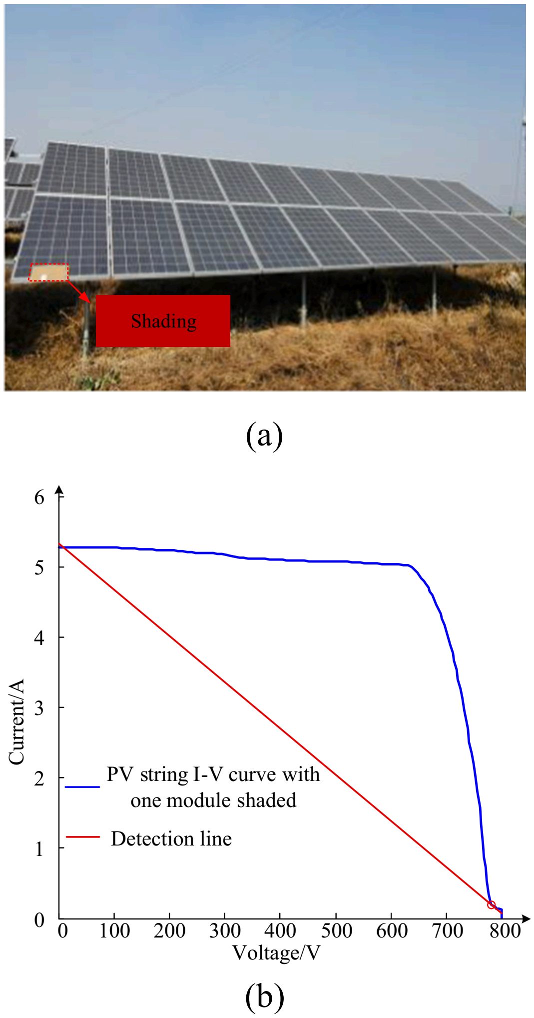

Fig. 10. Outdoor field test scene diagram and diagnostic results of the PV string with one module shaded. (a) Outdoor field test scene diagram. (b) Diagnostic results.

The fault diagnosis results of the samples and their actual fault types are counted, and the confusion matrix of the test results of the samples is shown in Fig. 11. The statistical indicators of the diagnostic method are calculated according to the confusion matrix to evaluate the performance of the fault diagnosis method. The fault diagnosis results are shown in Table 2.

From the diagnosis results, it can be seen that this method has a high accuracy. However, when the current mismatch in the string is very slight, such as a small shadow, the inflection point and step features on the I-V curve are not obvious, which will affect the accuracy of diagnosis.

5. Conclusion

As a common and serious fault type, PV string current mismatch fault greatly affects the reliability of the PV system. In this paper, a data-driven online diagnosis method for PV string current mismatch fault based on I-V curve is proposed. The PV string data can be conveniently obtained by using the I-V scanning function of the string inverter. The inflection point and step features appearing on the I-V curve of the string due to current mismatch are identified by constructing the detection line cluster, and the effectiveness of the method has been verified by the data of the field PV plant.

		Detected type	
		Non-mismatch	Mismatch
Actual type	Non-mismatch	200	0
	Mismatch	7	193

Fig. 11. Confusion matrix of sample test results.

Table 2
Fault diagnosis results.

Module type	Number of samples	Precision (%)	Recall (%)
Non-mismatch	200	96.6	100
Mismatch	200	100	96.5

CRediT authorship contribution statement

Zhixiang Zhang: Methodology, Conceptualization, Writing- Original draft preparation. **Mingyao Ma**: Funding acquisition, Project administration. **Wenting Ma**: Writing - Review & Editing, Investigation, Data curation. **Rui Zhang**: Formal analysis, Visualization. **Jun Wang**: Software, Validation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data that has been used is confidential.

Acknowledgements

Thanks to the funding support of the Project Supported by National Natural Science Foundation of China (Grant No.: 52061635101) and 111 Project (Grant No.: BP0719039). The authors would like to acknowledge the equipment provided by Sungrow Power Supply Co., Ltd.

References

[1] Z. Zhixiang, M. Mingyao, W. Hai, et al., A fault diagnosis method for photovoltaic module current mismatch based on numerical analysis and statistics, Sol. Energy 225 (2021) 221–236.
[2] S.P. Dhanup, N. Rajasekar, A comprehensive review on protection challenges and fault diagnosis in PV systems, Renew. Sust. Energ. Rev. 91 (2020) 18–40.
[3] S.R. Madeti, S.N. Singh, Online modular level fault detection algorithm for grid-tied and off-grid PV systems, Sol. Energy 157 (2017) 349–364.
[4] M. Dhimish, V. Holmes, B. Mehrdadi, et al., Photovoltaic fault detection algorithm based on theoretical curves modelling and fuzzy classification system, Energy 140 (2017) 276–290.
[5] S.A. Rahaman, T. Urmee, D.A. Parlevliet, PV system defects identification using remotely piloted aircraft (RPA) based infrared (IR) imaging: a review, Sol. Energy 206 (2020) 579–595.
[6] D. Adhya, S. Chatterjee, A.K. Chakraborty, Performance assessment of selective machine learning techniques for improved PV array fault diagnosis, Sustain. Energy Grids Netw. 29 (2022), 100582.
[7] IEC62446, Photovoltaic (PV) Systems-Requirements for Testing, Documentation and Maintenance, 2016.
[8] C. Zhicong, H. Fuchuan, W. Lijun, et al., Random forest based intelligent fault diagnosis for PV arrays using array voltage and string currents, Energy Convers. Manag. 178 (2018) 250–264.

[9] B. Li, C. Delpha, D. Diallo, et al., Application of artificial neural networks to photovoltaic fault detection and diagnosis: a review, Renew. Sust. Energ. Rev. 138 (2021), 110512.
[10] B. Rabah, M. Samir, Fault detection and diagnosis based on C4.5 decision tree algorithm for grid connected PV system, Sol. Energy 173 (2018) 610–634.
[11] L. Deng, Z. Dan, Z. Yi, et al., Simulation and comparison of centralized and distributed photovoltaic power generation system on MPPT, Chin. J. Electr. Eng. 13 (10) (2018) 41–46.
[12] R.B. Bollipo, S. Mikkili, P.K. Bonthagorla, Critical review on PV MPPT techniques: classical, intelligent and optimisation, IET Renew. Power Gener. 14 (9) (2020) 1433–1452.
[13] A. Mellit, G.M. Tina, S.A. Kalogirou, Fault detection and diagnosis methods for photovoltaic systems: a review, Renew. Sust. Energ. Rev. 91 (2018) 1–17.