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CHINA GENERAL CERTIFICATION

HUAWEI

Smart I-V Curve Diagnosis

Technical White Paper

Joint release by China General Certification Center

and Huawei Technologies Co., Ltd.

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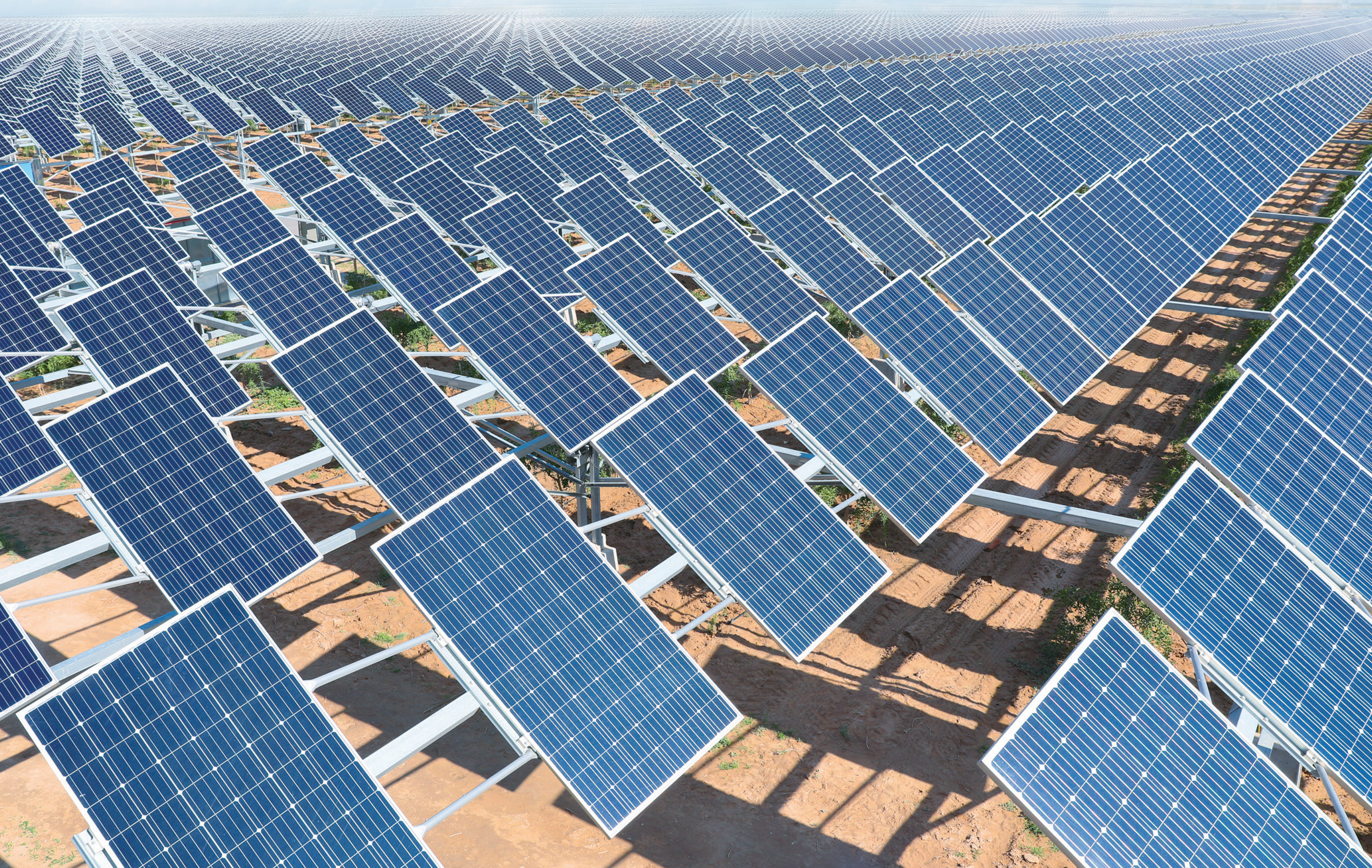


Preface

The Smart I-V Curve Diagnosis function provided by Huawei Technologies Co., Ltd. (Huawei for short) has entered the large-scale application phase. To date, this function has been applied to more than 7GW PV plants, featuring various site conditions, systems, and devices.

To verify the performance of this I-V scanning and smart diagnosis technology, Huawei entrusted the China General Certification Center (CGC) to conduct a technical review and a performance verification of the technology. The results confirm that Huawei-developed Smart I-V Curve Diagnosis technology reaches Level 4 (L4 for short), according to the CGC/GF 180:2020 "Technical Specifications for PV String I-V Scanning and Smart Diagnosis Evaluation" and IEC 62446-1: 2016 "Photovoltaic (PV) systems - Part 1: Grid connected systems - Documentation, commissioning tests and inspection." Put simply, the technology meets the application requirements.

CGC and Huawei have jointly released the *Technical White Paper on Smart I-V Curve Diagnosis* to enable the industry to better understand online I-V scanning and smart diagnosis technology. The white paper describes in detail the development background, technical features, and performance of existing technologies for I-V scanning and smart diagnosis, with the following aims:

(1) Provide reference for power plant development enterprises and other parties to accurately understand and use the Smart I-V Curve Diagnosis function.

(2) Provide a basis for enterprises that develop or apply the technology to improve their own technology based on current trends and changing application requirements.



01

Technology Development Background

A PV plant features a large number of PV modules and a wide footprint. For example, according to current PV module efficiency and system installation modes, a PV plant with an installed capacity of 50 MW occupies an area greater than 100 hectares and have more than 120,000 PV modules installed.

A PV module can be regarded as a small power generation device, and any PV module or electrical connection may become faulty. Figure 1-1 shows the typical electrical structure and potential fault types of a PV array using a string inverter.

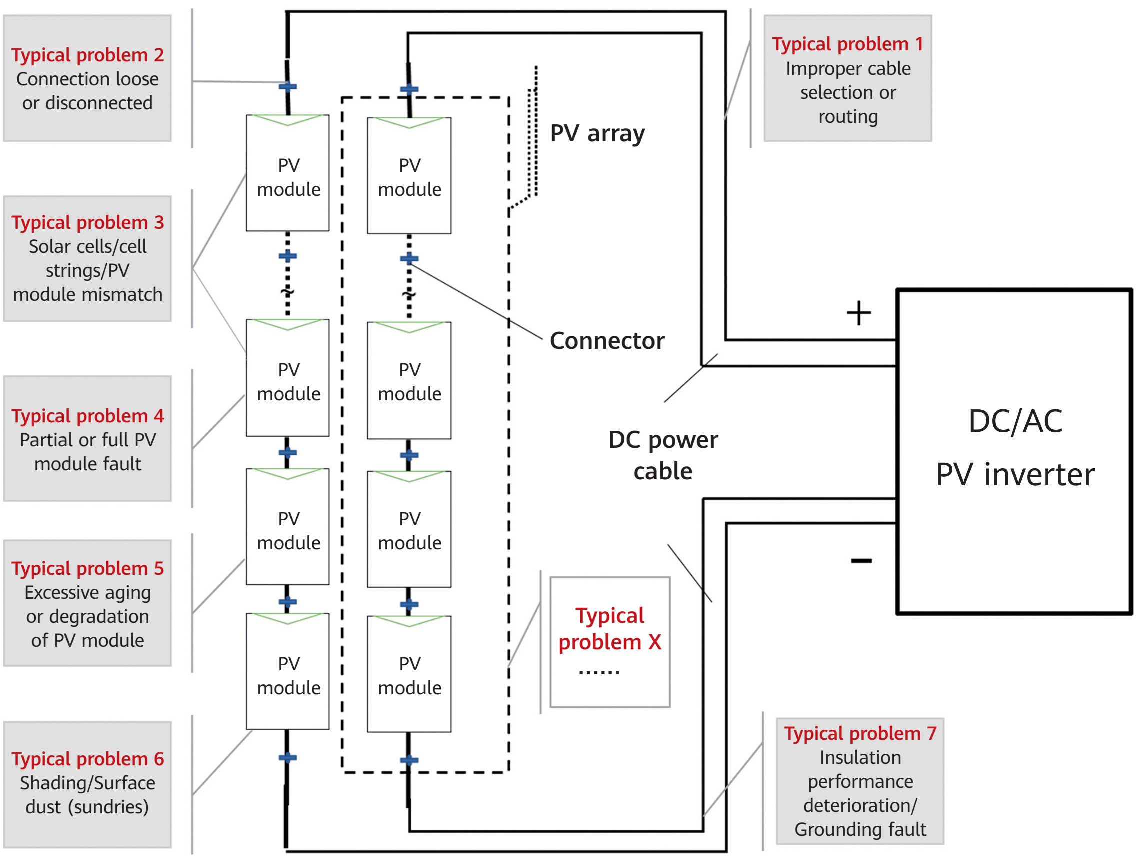


Figure 1-1 Typical electrical structure and potential fault types of a PV array using a string inverter

Various types of faults may occur at different locations throughout a PV system. Efficiently, rapidly, and accurately detecting and handling such faults during plant operation is one of the major challenges for plant O&M. Figure 1-2 and Figure 1-3 show the estimated energy yield loss in the statistical period based on CGC's test results of 150 sample PV plants. Although the data shown in the figures is not widely representative, it indicates that rapid detection and handling of the various faults that can occur during plant operation is the top priority of plant O&M.

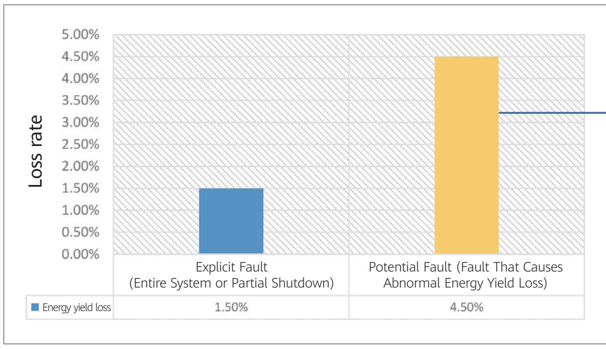


Figure 1-2 Energy yield loss due to faults

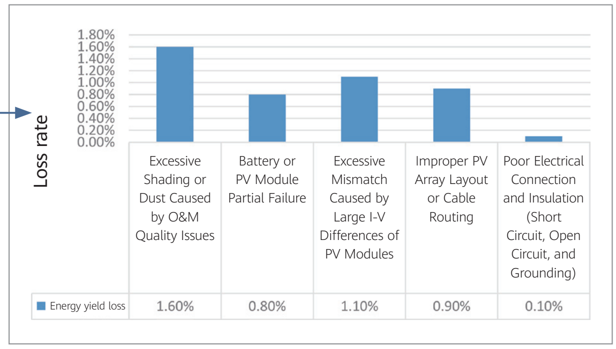


Figure 1-3 Types of energy yield losses due to potential faults

At present, fault detection for a PV system and its devices is primarily conducted using two modes: online and offline. The online mode is used to check and analyze the data in the management system, whereas the offline mode is used to perform manual inspection according to specified routes. Online inspection provided by the existing management system is still in the primary stages, and offers only limited fault information. Offline inspection cannot be thoroughly performed in most cases due to the features of PV plants. As a result, cutting-edge technologies, such as intelligent applications, are required to improve the efficiency and accuracy of PV system fault identification and to automate fault rectification.

For PV power generation, the ideal I-V outputs of PV modules, PV strings, and PV arrays result in an optimal

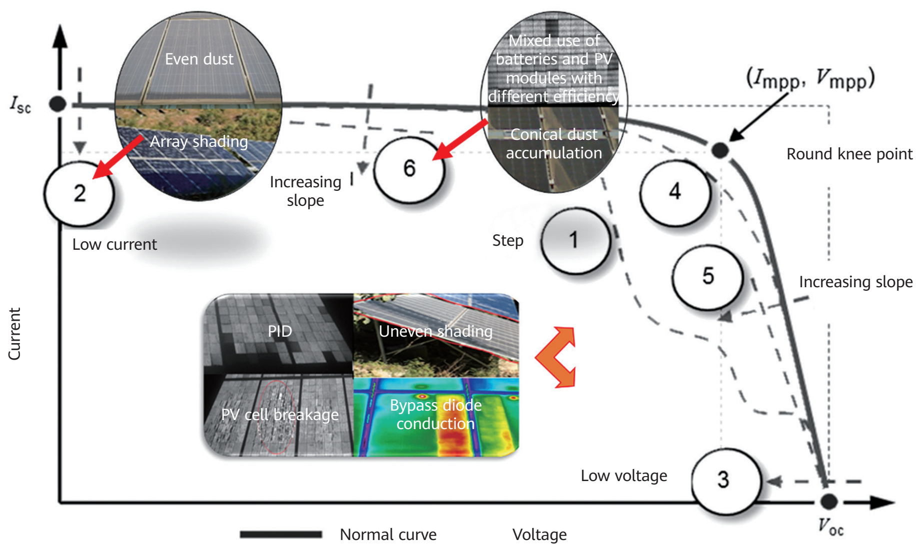


Figure 1-4 Mapping between abnormal PV string I-V symptoms and causes

power generation status. However, the I-V output changes if the operating environment and electrical devices (including connections) become abnormal. Figure 1-4 shows the mapping between abnormal I-V symptoms of PV strings and causes. As abnormal operating conditions and system (including device) faults have a strong mapping relationship with the PV string I-V output change, the PV string I-V monitoring result can be used to analyze and determine any problems that may exist during system operation.

Inverter maximum power point tracking (MPPT) is implemented by continuously measuring the output current and voltage of the PV array within the preset voltage range, and then determining the maximum power point through calculation and comparison. I-V curve scanning can be expanded to cover almost the entire scope (PV array or string level). Based on the preceding analysis, there is a strong need for online I-V measurement and fault diagnosis for PV strings by upgrading technologies and expanding functions based on the existing inverter MPPT technology. This is both technically feasible and economically practical.

02

Technical Description

2.1 Functions and Principles of Huawei Smart I-V Curve Diagnosis

Huawei Smart I-V Curve Diagnosis identifies the fault type of PV strings based on the current and voltage data collected by string inverters, big data mining, and AI identification algorithm. The Smart I-V Curve Diagnosis feature can be initiated in one-click mode, after which the Huawei SmartLogger (data logger) sends the I-V scanning command to the inverter. Once the complete I-V curve data of the PV string has been collected, the inverter uploads the data to the management system, which automatically generates a fault diagnosis report with its built-in fault diagnosis and identification algorithm.

In PV plant application scenarios, the I-V characteristic of a PV string is similar to that of the classic single-diode model. The relationship between the current and voltage can be expressed by the following formula:

$$I = I_L - I_0 \left\{ \exp\left[\frac{q(V + IR_s)}{nkT} \right] - 1 \right\} - \frac{V + IR_s}{R_{sh}}$$

The key electrical performance parameters in the preceding formula are described as follows:

- I: PV string operating current
- I_L: PV string photo-generated current
- I_0: diode reverse saturation current
- n: diode ideality factor
- V: PV string operating voltage
- R_s: PV string series resistance
- R_{sh}: PV string parallel resistance
- q: magnitude of charge of an electron
- k: Boltzmann constant
- T: thermodynamic temperature

The Huawei Smart I-V Curve Diagnosis feature is a product of iteration, and continuously evolves based on the classic diode model as well as massive PV string data from PV plants. The feature uses deep learning to determine possible PV string failure modes present in PV plant application scenarios, and establishes fault identification and diagnosis models for each failure mode which can be continuously upgraded and iterated on. The inverter reports the collected I-V curve to the I-V fault identification algorithm module of the management system, and the I-V algorithm module determines whether the PV string is faulty based on the current fault identification model.

In addition, to ensure the accuracy of the I-V scanning curve data and reduce the impact of environmental factors during the scanning, Huawei Smart I-V Curve Diagnosis feature embeds a stable algorithm into I-V curve collection, fault identification, and fault determination to improve the robustness of the I-V algorithm.

Based on the analysis of typical PV string I-V characteristic parameters, this feature can identify various defect information to determine whether PV strings are abnormal. For example, the I-V curve of the PV string is changed if a current mismatch occurs, as shown in Figure 2-1.

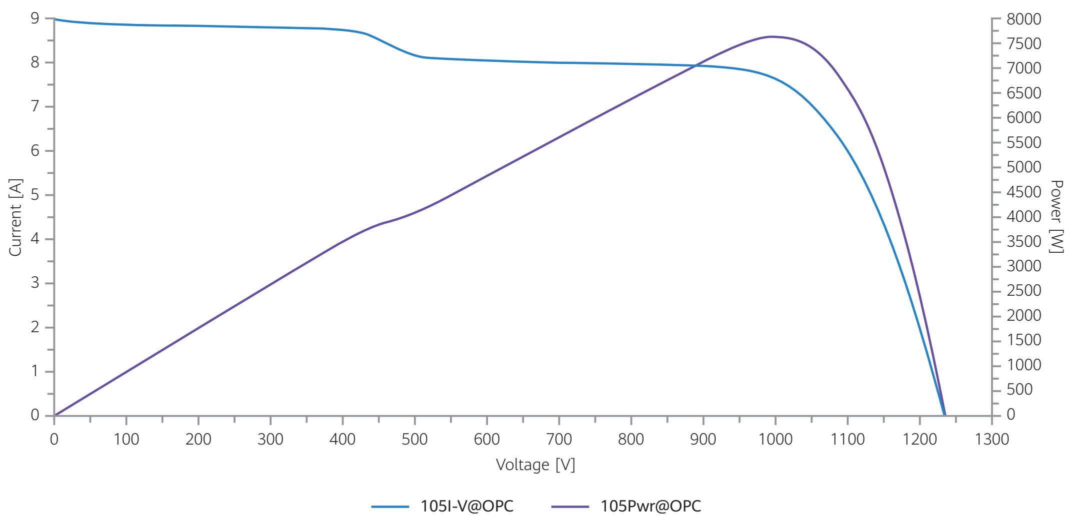
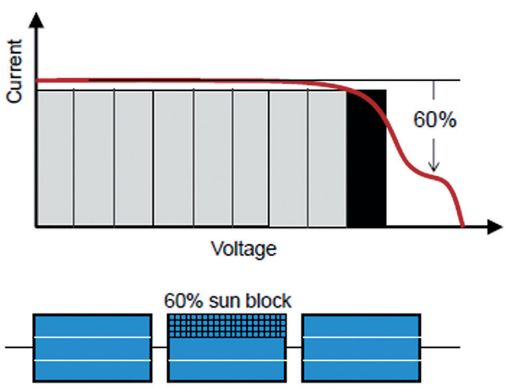
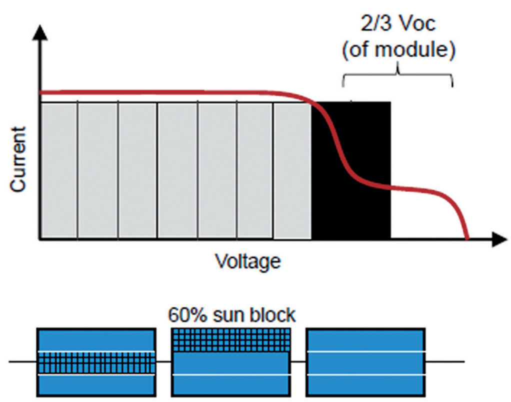


Figure 2-1 PV module current mismatch in a PV string



(a) One PV module shaded



(b) Two PV modules shaded

Each type of PV module fault in a PV string will leave a characteristic signal on the I-V curve. In addition, different types of PV module faults leave different signals on the I-V curve. These characteristic signals can be mined by using big data to accurately determine PV string faults.

Based on the preceding theories, Huawei Smart I-V Curve Diagnosis uses big data mining and AI identification algorithms to identify typical PV module faults and failure modes and generate alarms in PV plant application scenarios. Example fault types include:

1. Current mismatch in a PV string (due to shading, dust, or PV module current inconsistency)
2. Abnormal PV module output current (due to shading, glass breakage, or hot spots)
3. Abnormal PV string voltage (due to diode short-circuit or PV module failure)
4. Excessively low PV string parallel resistance (due to PID or dust)
5. PV string open circuit
6. Excessively high PV string series resistance (due to high cable impedance or abnormal PV module internal resistance)
7. Low PV string short-circuit current (due to abnormal orientation, dust, or PV module degradation)

The Huawei Smart I-V Curve Diagnosis feature automatically generates an I-V diagnosis O&M report after a plant scanning task is complete, providing different O&M suggestions for different fault types.

2.2 Technical Difficulties

For a large PV plant where PV strings are widely distributed, electrical performance data can easily be impacted by environmental conditions such as sunlight, temperature, and humidity, as well as device and system types. A major I-V curve diagnosis challenge is to quickly and accurately obtain the electrical performance data of PV strings and accurately identify PV string faults.

To reduce the impact of environmental factors on string I-V data collection and to ensure comparability of collected data, the inverter can scan data simultaneously, with a current and voltage detection precision of 0.5%. In addition, the inverter features a built-in curve collection algorithm to reduce the impact of environmental factors during scanning.

In terms of fault identification algorithms, Huawei uses the Smart I-V Curve Diagnosis algorithm to improve the accuracy and reproducibility of fault detection based on an in-depth understanding of PV module faults and failure mechanisms, data from 5 GW plant applications, and technologies such as big data mining, AI identification algorithms, and self-learning.

2.3 Huawei Solution and Technical Features

Huawei Smart I-V Curve Diagnosis consists of key elements such as the inverter, SmartLogger, and smart PV management system. The inverter collects the complete I-V data of all PV strings, and the SmartLogger uploads this data to the smart PV management system. The management system then uses its built-in PV string diagnosis and fault identification algorithm to detect all PV strings in a PV plant and identify any faults that may exist, thereby providing guidance for O&M. The following figure shows the overall solution.

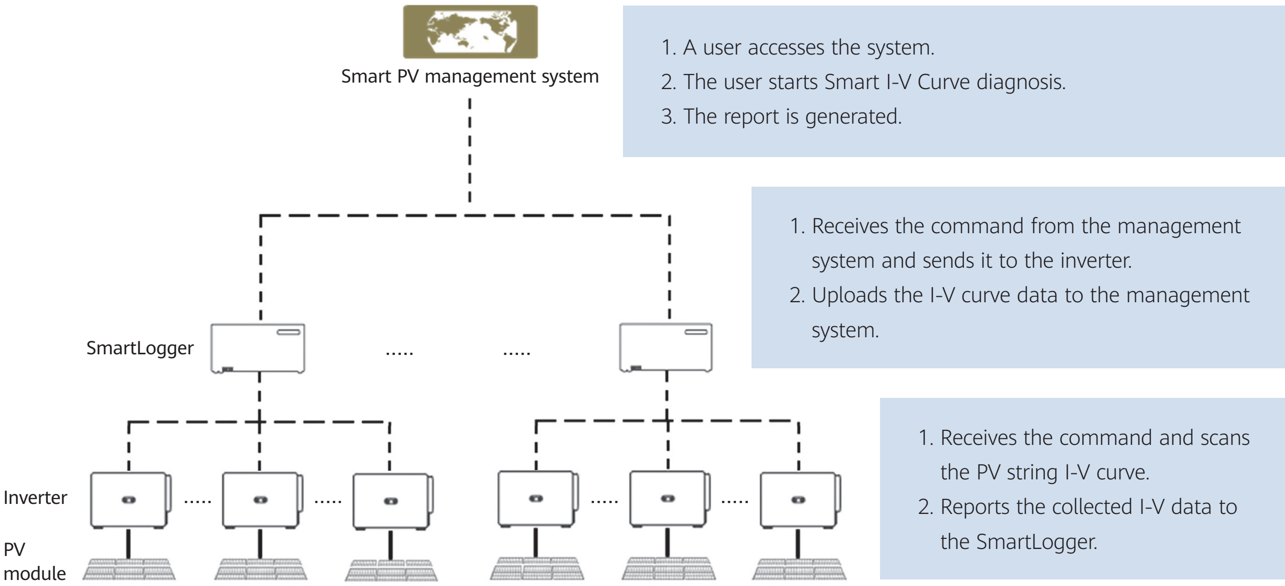


Figure 2-2 Networking of Huawei Smart I-V Curve Diagnosis

(1) Inverter: receives the scanning command from the management system, performs PV string I-V curve scanning, and uploads the I-V curve data to the management system through the data collector.

(2) SmartLogger: transparently transmits the command from the management system to the inverter, and uploads the PV string I-V curve data scanned by the inverter to the management system.

(3) Smart PV management system: supports plant-level parameter configuration, allows I-V diagnosis at the plant, array, and inverter levels, outputs diagnosis results and fault types, and supports the export of O&M reports to provide guidance for O&M.

03

Technical Verification and Evaluation

To comprehensively verify the performance of Huawei Smart I-V Curve Diagnosis, the CGC, as entrusted by Huawei, established a verification team to verify and evaluate the technology from February to July 2020. Figure 3-1 shows this verification and evaluation process, and Figure 3-2 shows the evaluation indicators and an example verification method.

Technical evaluation

Review items:

- Are the expected objectives of technology application clear? I-V scanning, exception identification, and fault diagnosis should be included.
- Is the applicable scope clear? Applicable device types (such as monofacial and bifacial PV modules; full cell, half-cut cell, and sliced cell PV modules), site conditions, and system forms (such as mountain or flat terrain conditions, fixed racking or trackers)
- Can the technical solution and software and hardware design achieve the expected objectives?

Review method: document review + onsite verification

→

Performance verification

Verification items:
See Figure 3-2.

Verification method: lab test + onsite verification (actual running conditions, simulated running environment)

→

Comprehensive evaluation

Evaluation items:

- Conformity and performance level of the technology and its performance with the existing standards and other normative documents
- Advancement and application prospect of the technology
- Improvement potential and direction of the technology

Figure 3-1 Verification and evaluation process

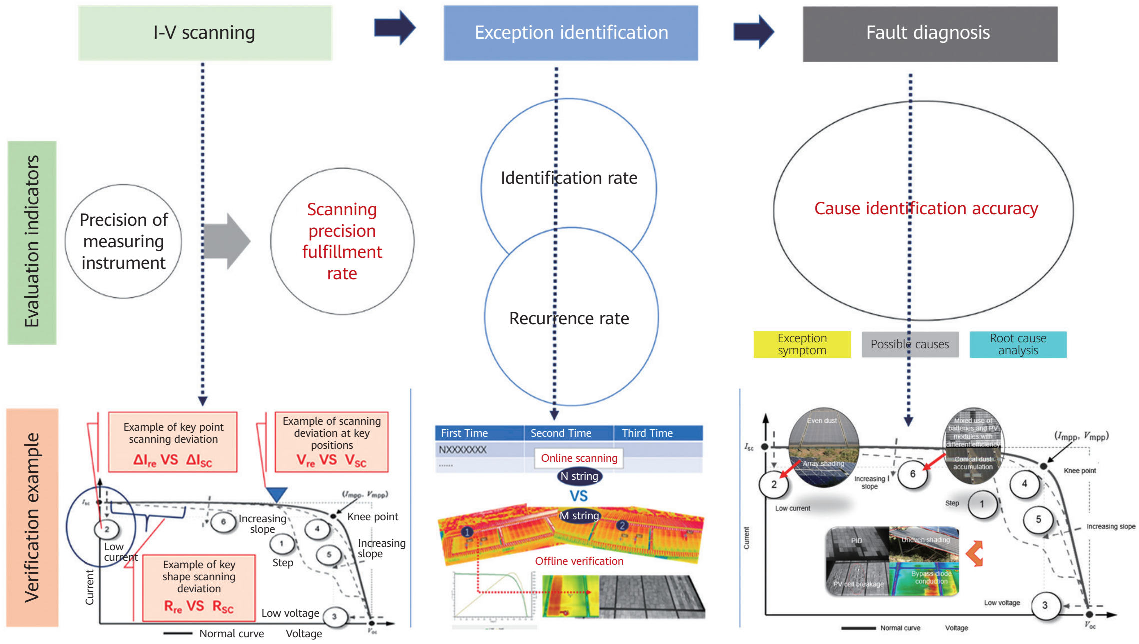


Figure 3-2 Evaluation indicators and example verification method

3.1 Technical Review Result

Huawei developed the Smart I-V Curve Diagnosis technology independently and is among the first to promote the technology within the industry. Following their review, the verification team concluded that the **technology meets the application requirements and applies to all system types and application scenarios. The technical solution is sound and can achieve the expected objectives, and it is anticipated that this technology will solve plant O&M difficulties.**

3.2 Performance Verification

Based on the explanation of the PV string I-V curve in IEC 62446-1: 2016 "Photovoltaic (PV) systems - Part 1: Grid connected systems - Documentation, commissioning tests and inspection," the CGC formulated the CGC/GF 180:2020 "Technical Specifications for PV String I-V Scanning and Smart Diagnosis Evaluation." Table 3-1 describes the verification items specified within, and Table 3-2 lists the performance rating standards for I-V scanning and smart diagnosis.

Table 3-1 Verification item description

Category	Verification Item	Description
I-V scanning	Precision of measuring instrument	Precision of the current and voltage measurement instruments for strings or arrays connected to the inverter
	Scanning precision fulfillment rate	Ratio of the number of PV strings whose key or selected points and sections meet the requirements after comparison between the online scanning fitting I-V curve and the standard measurement method test results, to the total number of sample PV strings
Exception identification	Identification rate	Ratio of the number of PV strings with abnormal I-V curves to the sum of the number of PV strings that are identified and the number of PV strings with abnormal I-V curve symptoms in the selected area
	Recurrence rate	Ratio of repeated identification at different points in time within the sample group before the cause of abnormal I-V strings is eliminated under similar operating conditions
Fault diagnosis	Cause identification accuracy	Ratio of the number of PV strings that meet the requirements after comparison between the scanning result of strings with abnormal (faulty) I-V curves and the standard method test results, to the total number of sample PV strings

Table 3-2 Performance rating standards

Performance Level	I-V Scanning		Exception Identification			Fault Diagnosis
	Measurement Precision	Scanning Precision Fulfillment Rate	Identification Rate		Recurrence Rate	Cause Identification Accuracy
			Type-I Defect	Type-II Defect		
L1	Voltage and current ≤ 1.0%	≥ 70%	≥ 75%	≥ 70%	≥ 70%	≥ 70%
L2	Voltage and current ≤ 1.0%	≥ 80%	≥ 85%	≥ 80%	≥ 80%	≥ 80%
L3	Voltage and current ≤ 0.5%	≥ 85%	≥ 90%	≥ 85%	≥ 85%	≥ 85%
L4	Voltage and current ≤ 0.5%	≥ 95%	≥ 95%	≥ 90%	≥ 90%	≥ 90%
L5	Reserved (for PV module type and system type extension)					
Comprehensive level: indicates the performance level that all indicators reach.						

According to the test results from the sample PV plants, the I-V diagnosis scanning precision fulfillment rate, identification rate, recurrence rate, and cause identification accuracy of the tested models all exceed 95%. As a result, the comprehensive performance level achieves L4.

3.3 Comprehensive Evaluation

Huawei Smart I-V Curve Diagnosis technology has now entered the large-scale application phase. Based on the technical review and performance verification results, this technology:

(1) Achieves the L4 comprehensive performance level according to the CGC/GF 180:2020 "Technical Specifications for PV String I-V Scanning and Smart Diagnosis Evaluation."

(2) Meets application requirements and applies to all system types and application scenarios. The technical solution is sound and can achieve the expected objectives, and it is anticipated that the successful application of this technology will solve plant O&M difficulties.

HUAWEI TECHNOLOGIES CO., LTD.
Huawei Industrial Base
Bantian Longgang
Shenzhen 518129, P. R. China
Tel: +86-755-28780808
www.huawei.com