Introduction of
Huawei Smart I-V Curve Diagnosis

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Huawei Technologies Co., Ltd.

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Content

1 Overview

With the wide and rapid deployment of PV plants around the world, the industry will step into Terawatt era in the middle of 2020s and more and more attentions have been already paid to the operation of PV plants than the early-stage construction and commission. Failures and faults are the most common issues in the PV plant. Most of them at AC side can be easily confirmed and recovered since the O&M companies have rich experience in thermal power and hydropower that can be transferred to PV O&M. But at DC side it seems to be impossible to inspect and recover the faults and failures. On one hand it is because of the lack of experience of O&M people in the maintenance of DC equipment. On the other hand, it is due to the huge quantity of devices and the lack of DC O&M experience. Therefore, most of faulted or failed modules remained untreated in the PV plant, resulting in the loss of generation energy, the increased risk of safety and hence the high risk of asset and investment.

In the year of 2016, based on the leading technology of string inverter and the understanding of AI technology, Huawei solar business released a revolutionary function, Smart I-V Curve Diagnosis, to help the customers deal with the DC side inspection. Through 4 year online running, Smart I-V Curve Diagnosis has become one of the most powerful tools against difficult O&M and energy loss, which has 5 GW application and was awarded Terawatt Diamond Award, SNEC Top 10 Highest Award.

This document is the introduction of Huawei Smart I-V Curve Diagnosis, aiming to elaborate the failure of PV modules, I-V curve testing, mechanism of Huawei Smart I-V Curve Diagnosis function and the value for customers.

2 PV Module

A PV system generally contains PV modules, racks, cables and terminals at DC side, among which PV modules are the main component that generates power and hence have the most important influence on the power loss when failures or faults occur. This section is to introduce the mechanism on how PV modules work, the faults and failures associated with PV modules and the on-site testing methodology.

2.1 PV Module in the Entire PV System

PV module (also called solar panel) is the essential and the most important part of the PV system, a fundamental unit of PV system (or photovoltaic device) that converts solar energy into electrical energy, which is then stored in a storage battery or used to drive loads. In actual PV plant applications, multiple PV modules are connected in series to form a PV string, and then one or more PV strings are connected in parallel to an inverter that converts DC power into AC power.

Like most semiconductor devices, the output power characteristics of the PV modules are determined by many factors such as the PV module status, external light intensity, ambient temperature, etc. When the PV modules are working, the output power decreases due to faults, light-induced degradation, reduction of the received light intensity because of shading or small illumination angle, increase of the working temperature of the PV modules in poor heat transfer conditions. As a result, the output power of one module decreases. Furthermore, the PV modules with low power generally cause the mismatch loss of the entire string and the energy generation of the overall PV plant is further reduced.

2.2 Fault Types of PV Modules

PV modules degrade due to various external factors (UV, humidity, temperature, mechanical stress, and so on). The failure rate of PV modules shows a U-shape curve during the life cycle and is generally divided into three phases: infant, middle, and wear-out. The fault rate of PV modules varies in the entire running period, as shown in Figure 2.1.

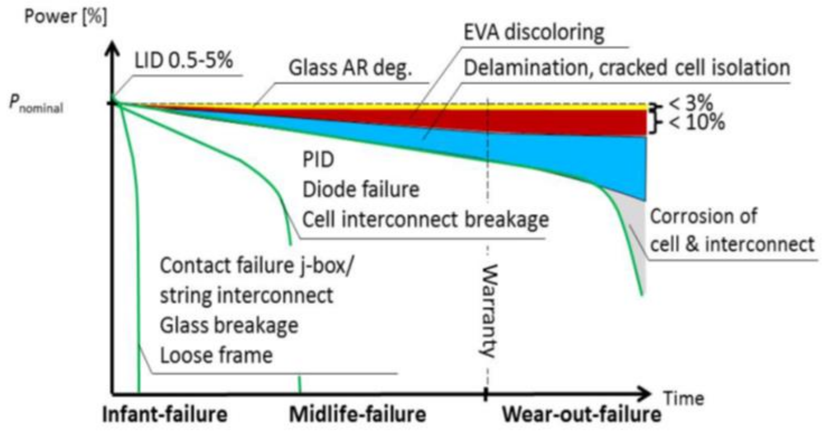


Figure 2.1 Failure rate of PV modules in the entire life cycle

At the infant stage, faults of PV modules are usually caused by serious quality problems, such as fast degradation of module, crack, etc., which will cause the rapid decrease of output power of the PV modules. The performance of PV modules is typically stable in the middle period of operation and the performance degradation caused by faults is usually linear. PV module faults at the end of operation are usually caused by material aging. The impact on the output power of PV modules directly determines the operating life of the PV plant.

In practice, the typical faults of PV modules are the following, as is shown in Figure 2.2.

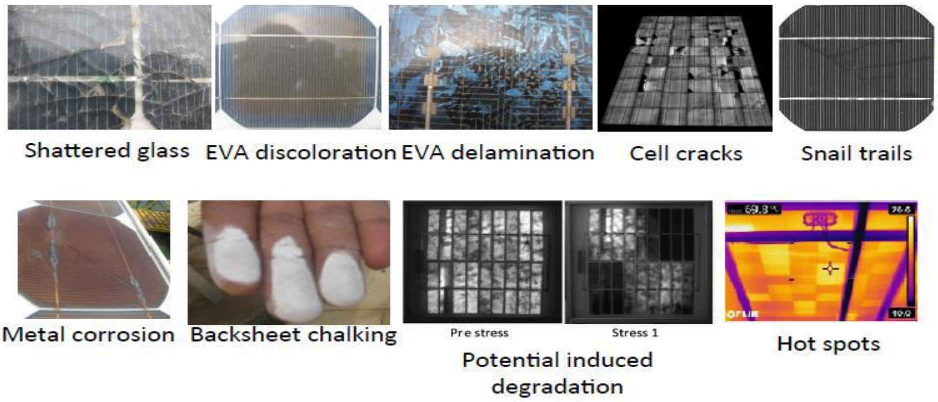


Figure 2.2 Fault types of PV modules

Shattered glass: Glass breakage due to quality or environmental causes such as bump by a flying granular. Shattered glass not only has impact on the output power of one module but also cause the mismatch loss of the string(s) containing this module. More important is the increased risk of safety because the isolation level decreases largely when the glass is broken. It is easy to cause electric shock in a rainy day or when water remains on the module surface. Therefore, when glass breakage happens to a module, please replace it as soon as possible in a safe way.

EVA discoloration and delamination: EVA failure due to EVA quality or the encapsulation process, which will lead to the decrease of incident light into the module and hence reduce the output power.

Cell cracks: Cell crack is the most common failure due to poor transportation or installation, which has very strong impact on the power output of a module. Such kind of modules should be replaced immediately. However, it is too difficult to find out all the modules with cell crack in the plant. Even for 0.1%, no inexpensive approach is available. Sometimes cell crack is not obvious and is thus called hidden cracks. Both crack and hidden crack are of high risk for the entire plant because they can both lead to the hotspot and probably the firing of modules.

Potential induced degradation (PID): Some PV modules in a PV system have a negative potential to earth and also have this negative potential to the earthed mounting system. Due to this potential difference, anode ion (generally Na^+ ion) flows from the glass plate into the semiconductor material of the solar cell, and contaminate the cell. These Na^+ ion have a strong negative influence on the performance of the PV cell (Polarization). As a result, solar cells become inactive and generate less electricity. One cause people are inclined to acknowledge is temperature & humidity. The degree of PID effects activity varies with the temperature & humidity level. Degradation is also related to the degree of contamination of the glass plate caused by objects that are electrically conductive, acidic, alkaline, or ionic. PID is the cancer of PV module and it must be avoided.

Snail trails: Snail trails is caused by the hidden crack which causes the oxidation of silver around hidden cracks. Snail trails may induce the rapid degradation of PV module.

Metal corrosion: Metal corrosion is the result of the oxidation of metal interconnection in a humid environment after the water invades into the module capsulation. As a result, the resistance of the module increases largely and the performance is reduced dramatically. Moreover, when this module is connected in the string, it causes the deleterious effect on the string performance by introducing mismatch.

Backsheet chalking: Backsheet chalking stems from the quality of backsheet that causes the invasion of water into module, which indicates probable PID and metal corrosion as a result.

Hot spots: When shading or non-uniformity occurs on one module, there is very high reverse-bias across a very small region, which causes high temperature and the so-called hotspot. When the hotspot lasts for a period, the breakdown of the solar cell encapsulated inside the module occurs, which probably leads to the fire.

2.3 Introduction of On-site Inspection of PV Modules

There are several on-site approaches of inspecting and testing the PV modules that can directly test the modules in the PV plant without carrying these modules to laboratory.

Visual inspection
By means of visual inspection, glass breakage and disconnection of one string can be found out and then recovered. However, the quantity of modules is too large for O&M people to inspect. Therefore, this method is typically for occasional use.

Thermal image
Thermal image is the approach to detect some internal faults of PV modules by means of infrared camera. Hotspot and diode short-circuit are the most common faults that can be detected by thermal image. But thermal image is unable to detect other faults or failures like abnormal degradation and mismatch. This method is also for occasional use for the similar reason of visual inspection.
Recently, technologies combining visual inspection, thermal image and drone have been developed to be automatic approach for the inspection, which is believe to the future of O&M.

I-V curve
I-V curve is one of the effective approaches that can detect the electrical faults of one module or string. Any electrical abnormal can be recognized through I-V curve. Recently, more and more investors and developers are requiring I-V curve testing to be conducted during the commissioning of plants in order to assess the overall health of the plant from the beginning.
For traditional I-V curve testing, specific equipment is required for offline testing. The

procedure is shown in Figure 2.3. In practice, 0.1%-10% of the modules and/or 5%-50% of strings will be selected for testing by random. Two professionals firstly shut down the inverter/DC box, disconnect the target module/string by unplugging the terminals, connect the module/string to the device, operate the device, record the results and reconnect the module/string to the inverter/DC box. Professionals do the analysis afterward and output the diagnosis report. Typically, 1MWp plant with 1% module sampling or 10% string sampling needs 1~2 man-days to output the report, which is indeed dependent on the plant size and plant type.

The disadvantages of this traditional approach is low sampling rate, poor data quality due to uncertainty of testing, inconvenience and high safety risk for rooftop, mountain and lake plants and high cost for labors. Additional risk relies on the unplug action of the strings from inverter before traditional I-V testing, which will probably cause terminal damage and bring in high risk of arc.

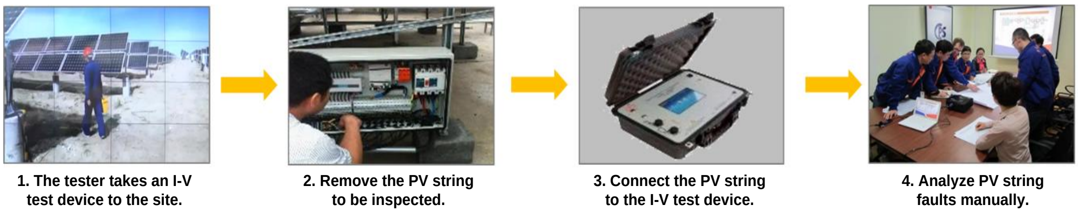


Figure 2.3 Traditional offline I-V test

Electroluminescence (EL)

EL means PV module under exitation can emit near-band infrared light. With the help of high-resolution IR camera, EL can help detect module quality issues such as cracks, PID and diode issues. In practice, EL is carried out at night to avoid interference of visible light and a power source is required for EL to exite one PV module/string, with the infrared images outputed in Figure 2.4.

Tradition on-site EL requires two professionals, EL camera, very heavy portable power bank and some accessories. Typically, 1MWp plant with 1% module sampling needs >2 man-days to output the report. Therefore, the disadvantages of traditional EL is similar to that of I-V curve.

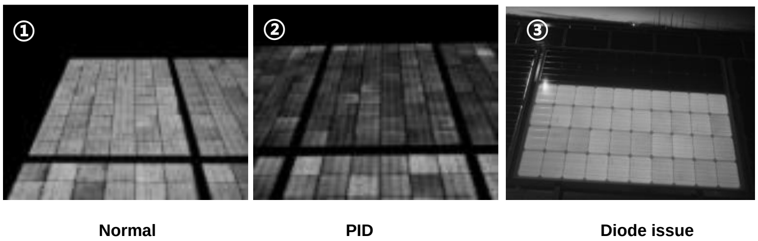


Figure 2.4 EL test

To summerize, the state-of-art inspection methods, including visual inspection, thermal image, I-V curve and EL, all have the disadvantages of inconvenience and high cost due to repetitive testing in order to identify the exact location and root cause relating to panel faults. The cost-effectiveness of these methods should be estimated case by case in order to determine whether one or several of these methods are needed.

3 Huawei Smart I-V Curve Diagnosis

In 2016, as a result of joint innovation with Huanghe Hydropower Company (one subsidiary company of State Power Investment Corporation), Huawei released Smart I-V Curve Diagnosis online, which then became the hot sale in the market. In the past four years, this feature has evolved from version 1.0 to version 3.0 and has been sold by around 5GW around world. In 2020, version 4.0 will be released with more advanced and customized functions and most inverters released after 2016 support update to the latest version (For details, please refer to Huawei sales team).

In this chapter, a dedicated description will be aiming to demonstrate the mechanism and the function of Huawei Smart I-V Curve Diagnosis.

3.1 Mechanism

3.1.1 Mechanism for String I-V Scanning

String I-V Curve scanning with high-precision can be achieved through high-precision signal sampling and voltage/current controlling during fast scanning. After receiving the command of I-V scanning, the inverter(s) will

(1) Control each MPPT to go to open-circuit point separately, as is shown in Figure 3.1.

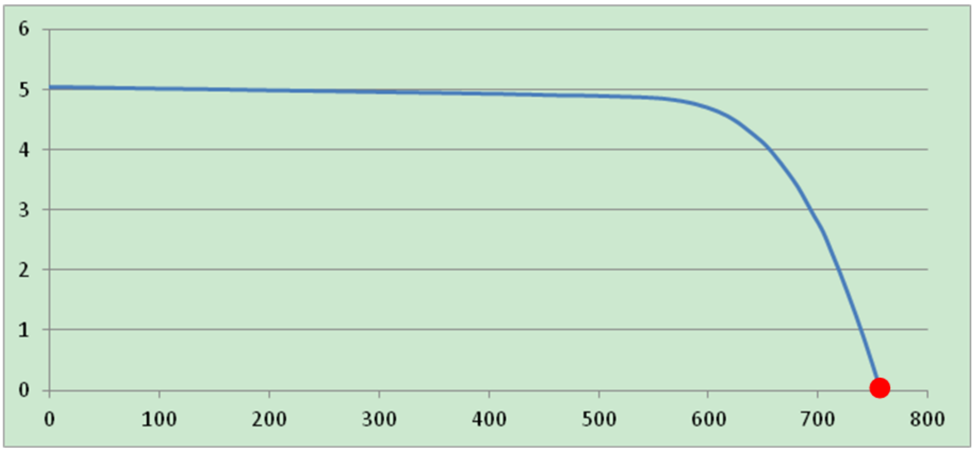


Figure 3.1 MPPT at the open-circuit point

(2) Reduce the string voltage linearly and collect voltage and current values simultaneously, as is shown in Figure 3.2.

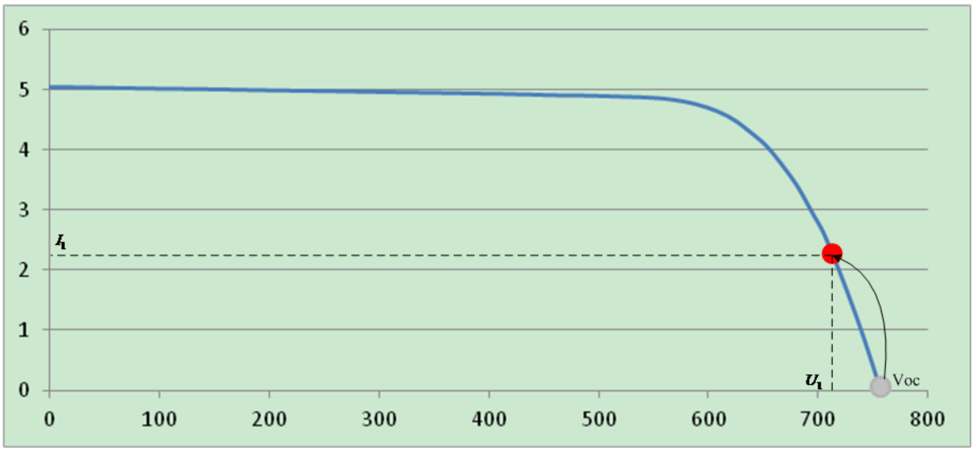


Figure 3.2 Status during voltage decreasing

(3) Repeat voltage decreasing and data collecting until V is close to 0 (not equal to 0) for a whole I-V curve and the corresponding data, as is shown in Figure 3.3.

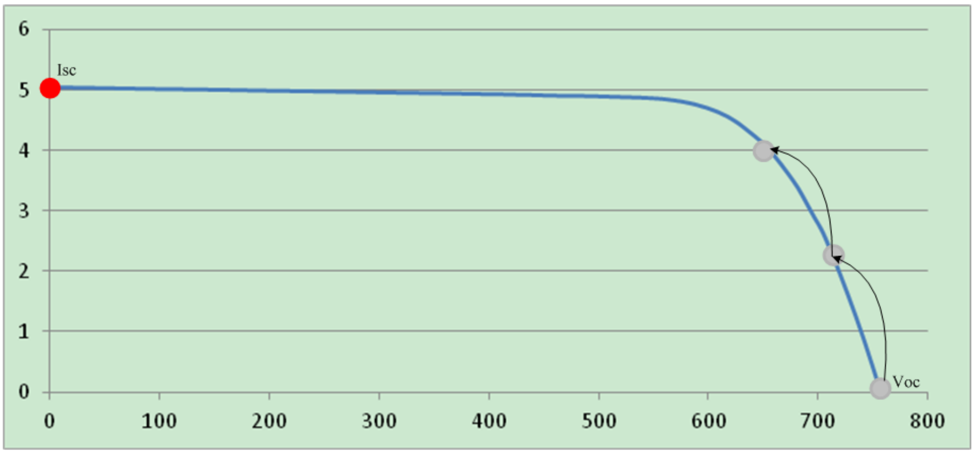


Figure 3.3 Status when voltage is close to 0

(4) Above is the reverse string scanning, after which there will be a forward scanning from the point close to short-circuit to the point of open-circuit, in order to increase the precision of data. This is because there is capacitor effect during the scanning and the combination of reverse and forward scannings can eliminate this negative effect by data governance.

3.1.2 Mechanism for Diagnosis

The Diagnosis is carried out based on the assumption that most of the PV modules are unlikely to have one particular fault. Therefore, the “true” irradiance and module temperature for the solar cells encapsulated in the module can be calculated according to the effective data collected during I-V curve scanning and uploaded to Huawei management system, which will then compare the data with built-in physical models and judge whether there is fault or not in the strings through mode recognition with the trained AI model built in.

Any type of faults related to electrical performance has their unique signals. After translating string I-V curve features to characteristics, it is easy to determine whether strings are abnormal and the causes behind them.

Example 1: string I-V curve will introduce notches when there is current mismatch, as is show in Figure 3.4.

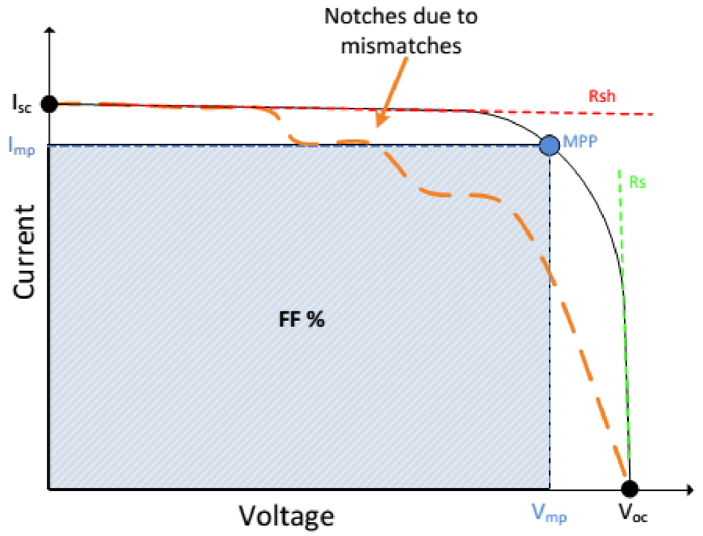
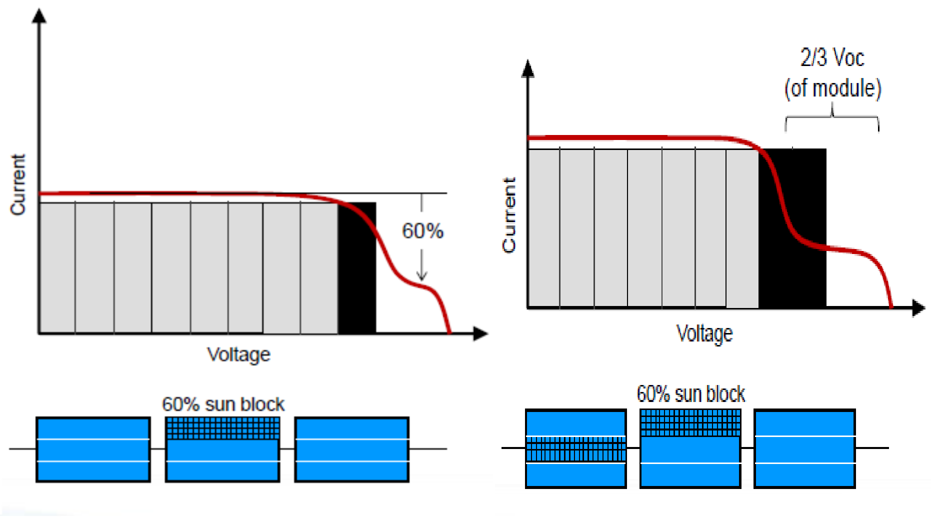


Figure 3.4 Typical I-V curve for strings with current mismatch

Example 2: If one or more modules are shaded, the I-V curves change a lot with obvious power reduction at the high voltage range, as is shown in Figure 3.5.



(a) One sub-module shaded (b) Two sub-modules shaded

Figure 3.5 Typical I-V curve for strings with one or more units in shadow.

3.2 **Solution of Smart I-V Curve Diagnosis**

The solution of Smart I-V Curve Diagnosis comprises the data collection at inverter side, data transportation through SmartLogger and diagnosis integrated in Huawei management system, which follows the standard device-pipe-cloud topology. As is shown in Figure 3.6,

1) Device: Inverter (SUN2000/SUN2000HA*) with a license for Smart I-V Curve Diagnosis

Inverter receives the command of scanning, implement the command, collect I-V data and send them to SmartLogger.

*Inverters released after 2016 typically support Smart I-V Curve Diagnosis while older inverters fail to be upgraded.

2) Pipe: SmartLogger (SmartLogger1000/SmartLogger2000/SmartLogger3000)

SmartLogger receives commands from management system, dispatch them to inverters and then receives the data collected by inverters and uploads the data to management system.

3) Cloud: Huawei management system (NetEco 1000S or the coming FusionSolar 7.0)

Huawei management system is the platform where the plant-level, array-level or inverter-level diagnosis starts. In the management system, one can fill in and modify the parameters for I-V curve scanning. After one-click, the management system can output the diagnosis results with fault statistics and original I-V data.

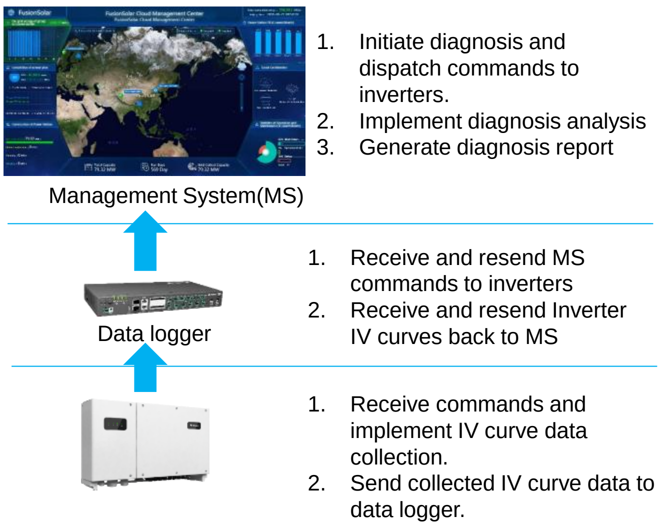


Figure 3.6 Typical I-V curve for strings with one or more units in shadow.

3.3 Specifications of Smart I-V Curve Diagnosis

To achieve high presion diagnosis without the assist of external meters, Smart I-V Curve Diagnosis has some technical requirements.

1) Illumination: Stable illumination >400W/m^2 is the minimal requiement for I-V scanning. The higher the illumination, the better the data quality.
2) Accuracy of data: Smart I-V Curve Diagnosis is developed based on the machine learning, the fundamental of which is the quality of data. This indicates that the sensors should be of high accuracy.
3) Scan speed: The I-V data should be obtained in a steady condition and is typically interfered by atmosphere variation, such as wind and sunlight. The only option for on-site testing is to create a quasi-steady state for scan during a very short period to avoid environment variation. Therefore, the scan speed should be very fast. Besides, condiering the capacitor effect of high-efficiency modules, the scan speed should be no less than 100 ms.
4) Synchronization: Since the diagnosis after scanning requires string-string comparisons, synchronization of string scanning can ensure the comparability of I-V curves.
5) Resolution: Data points for one I-V curve is no less than 100 to keep the I-V curve as smooth as possible.
6) Experience: In the diagnosis report, the faulted string and the cause of fault should be

clearly denoted.

Based on these requirements, Huawei developed its Smart I-V Curve Diagnosis, whose specifications are listed in Table 3.1. To enhance the experience, Smart I-V Curve Diagnosisis is designed to complete the scan and diagnosis within 15 min for a 100MW plant. Moreover, the compatiblity of I-V scanning is improved to deal with complex cases such as bifacial module, Y-connector, reservation, etc.

Table 3.1 Specifications of Smart I-V Curve Diagnosis

Items	Specifications
Scan speed	＜1s for one scan for one string
	<25s for one 185KTL inverter (9 MPPT)
	<15min for 100 MW
Scan resolution	128 points
Scan accuracy	Voltage/Current ≤0.5%
Scan convenience	Online operation and one-click for a plant
Scan consistency	>200 strings at the same time (If total string number is >200)
Scan footprint	All selected strings
Analysis & Report	Automatic analysis and fault confirmation report
Energy loss	≈0kWh
Compatibility to modules	All, including bifacial, Shingle, Half-cell, etc.
Others	Y-connector compatible, reservation for diagnosis, O&M advisor, etc.

3.4 **Output of Smart I-V Curve Diagnosis**

There are *four* output documents after diagnosis: *detection report*, *diagnostic report*, *O&M report* and *original data*. As is shown in Table 3.2, Smart I-V Curve Diagnosis can recognize 14 kinds of faults and possible fault causes, which are verified by TUV.

Table 3.2 Faults and possible causes in diagnostic report

No.	Fault	Possible causes of failure
1	PV string open circuit	PV string breakage/PV string configured by mistake
2	Current mismatch in the PV string	Shade/dust/PV module current inconsistent
3	Abnormal PV module output current	Shade/glass breakage/hidden crack
4	Abnormal PV string voltage	Diode short circuit/PV module invalid/PV module quantity incorrect
5	Low PV string short-circuit current	Abnormal orientation/dust/PV module degradation
6	Low PV string power	Abnormal orientation/dust/PV module degradation
7	No string connected	Check whether PV strings are connected to the inverter
8	Missing configurations of PV strings	Check whether string information is configured in the system
9	Excessively low irradiance	The solar radiation is insufficient

		(Analyzed the data sent by HW inverter)
10	Slight current mismatch in the PV string	Dust/slight shade/glass breakage
11	Excessively low PV string parallel resistance	PID degradation/dust/uneven PV module irradiance
12	Excessively high PV string series resistance	High cable resistance/abnormal internal resistance of the PV module
13	Abnormal curve near MPP in the PV string	Hotspot/hidden crack/glass breakage
14	Scanning data invalid	Irradiation cause

The O&M report provides the exact location of strings with faults inlcuding suggestions for the customers to assess and confirm the faults.

All the above faults should be fixed but there should be priority for faults causing system risk and/or higher yield loss. In Table 3.3, the impacts of faults on yield and system security are demonstrated, which are referred to give O&M suggestions in Huawei management system. For example, if “Abnormal PV module output current” occurs in diagnosis report, the cause with the highest possibility is breakage of glass. Since this can take O&M in risk, the suggested O&M strategy will be “replace the module”. If “Slight current mismatch in string” occurs, take it as minority issues and just keep on watching the evolution of such faults.

Table 3.3 Faults and their impacts

Fault Type	Impact on Yield	DC security risk	Possibility of occurrence
PV string open circuit	100% for each string	Risk of electric shock in O&M	High
Current mismatch in string (Dust)	3-30% for each string	Severe blockage causes hotspot risks and modules reliability degrades	High
Abnormal PV module output current (Breakage)	>5% for each string	Energy yield loss, modules reliability risks, and safety risk in O&M	Very High
Current mismatch in string (Shade)	1-5% for each string	Same with the dust	Very High
Slight current mismatch in string (Slight shade)	1-4% for each string	Maybe there is dust, shade or other problems	Very High
String connection reverse	100% for each string	Risk of electric shock in O&M	Very Low
Low PV string power(PV module degradation)	3-7% for the whole plant	Module reliability degrades	Inevitable
Abnormal PV string voltage(Diode short circuit)	~1.1-1.5% for each string	Module reliability degrades	High
Abnormal PV string voltage (PV module invalid)	0.5-0.7% for each string	The string information may not be configured successfully in system	Very Low
Low PV string power (Abnormal orientation)	0.5-0.7% for each string	Inherent problems in PV plant design and cause energy yield loss	Very Low
Excessively low PV string parallel resistance (PID)	5-50% for the whole plant	Affecting the service life of the modules.	High temperature, humidity& salinity Scenario
Abnormal curve near MPP (Hotspot)	0.01% for each module hotspot	Risk of fire, accelerating aging, etc.	Very High
Excessively high PV string series resistance (High cable resistance)	0.5-5% for the whole plant	Fire risk caused by DC arcing	Low
Abnormal PV module output current (Hidden crack)	Uncertain	Hot spot risks that degrade reliability	Very High

4 How to Use Smart I-V Curve Diagnosis

This chapter is devoted to description on how to operate Smart I-V Curve Diagnosis and how to read diagnosis report and make O&M Decision, which will take one reference plant in Asia as example.

4.1 Start the Diagnosis and Output the Reports

4.1.1 Requirements

All of the following conditions should be met to ensure normal PV string diagnosis; otherwise, scanning will fail or misdiagnosis may occur.

- The license for Smart I-V Curve Diagnosis is valid. Otherwise, one can ask for help from Huawei engineer team. For details, see the *Smart I-V Curve Diagnosis User Manual*.
- The day is sunny with stable sunlight. The irradiance is > 400 W/m^2.
- The cleaning status is consistent for a diagnosis task.
- The PV modules are clean and dry. Recommended: start the function after PV modules are cleaned or heavy rain has stopped.
- The PV modules connected to the same inverter have identical type and model. Every PV string has the same number of PV modules connected in series.

4.1.2 Operation

This part can refer to Chapter 4 of *Smart I-V Curve Diagnosis Technical White Paper*. Please ask Huawei sales team for this material.

4.2 Review of Diagnostic Report and Make an Informed O&M Decision

As is shown in Figure 4.1, there are four documents as output of Smart I-V Curve Diagnosis, Detection report, Diagnosis report, O&M report and original data spread sheet.

Detection report contains the plant information, evaluation of the PV string failure rate and fault type analysis.

Diagnostic report contains information of scanning task, overview on diagnosis, PV string I-V curve details and PV string performance data details.

O&M report contains information of task, overview on diagnosis and following advice on maintenance.

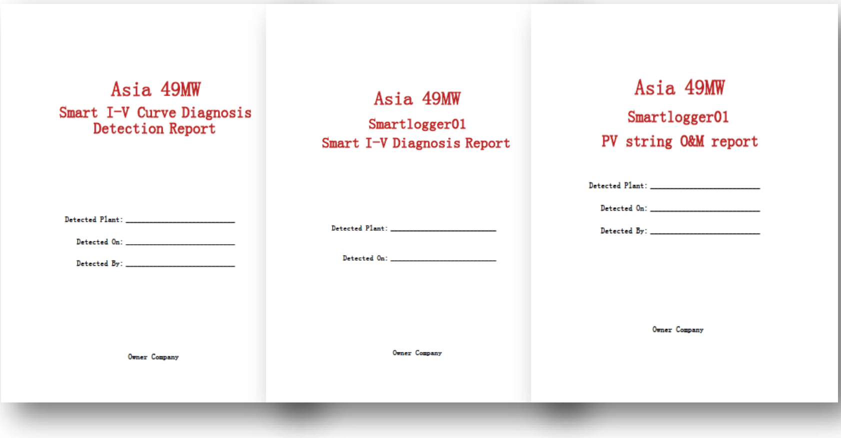


Figure 4.1 Output of Smart I-V Curve Diagnosis

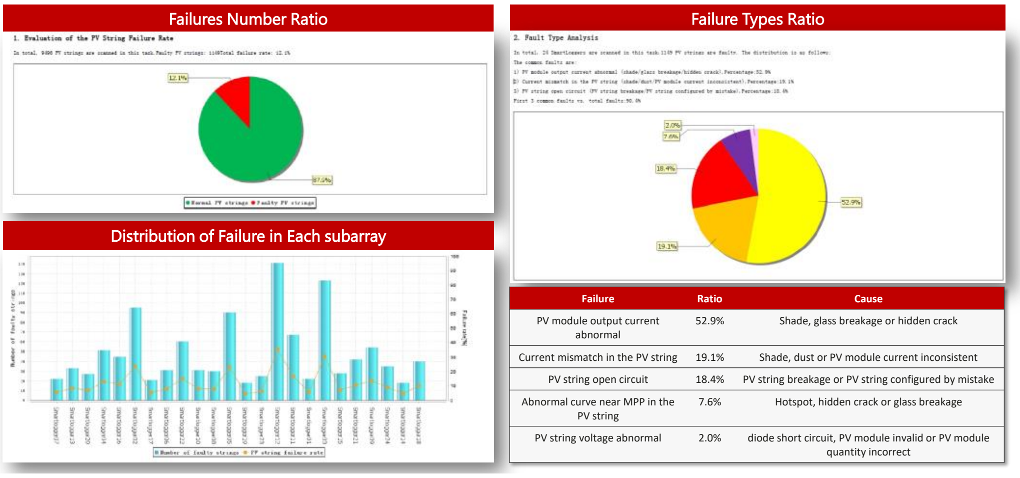


Figure 4.2 Statistics in Detection report

In practice, Detection report, as is shown in Figure 4.2, is used as a summary of the state of health at the DC side in a PV plant, which might be useful for asset management. O&M report is the guide for O&M people to confirm the faults mentioned in the report and recover the faults. For further information, one can turn to Diagnosis report and original data spread sheet which include more details such as I-V curve of each string with 128 points, STC performance of each string that is translated from raw data, etc. For routine O&M, 3-4 times/year is suggested. The function of reservation for Smart I-V Curve Diagnosis is preferred for 0-touch experience, which can provide an automatic output of diagnosis report.

For advanced application, one can compare the string STC performance to the theoretical value to investigate the degradation behavior of modules, which may serve as the guide for plant design in the future. Otherwise, the STC performance can be used to study the real-time soiling performance when there is a clean reference, which is helpful to guide the strategy for routine cleaning.

In Smart I-V Curve Diagnosis 4.0, there will be function update called "O&M advisor". All the faults will be sorted by their urgency and impact on yield loss and thus given the priority for recovery, as is described in Chapter 3. O&M people can make their decisions based on this reference.

4.3 **Case Study**

Plant size: 50MW

Plant location: Southeast Asia

Plant introduction: Mountain, complex terrain and difficult O&M.

Figure 4.3 Top view of the PV plant for Smart I-V Curve Diagnosis

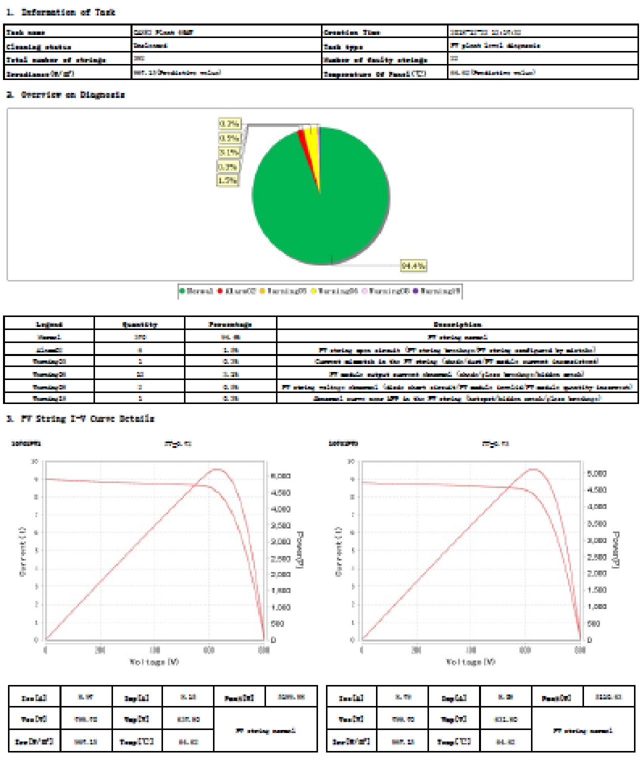


Figure 4.4 Diagnosis report of the abovementioned PV plant

After inspection with Huawei Smart I-V Curve Diagnosis, Figure 4.4 shows the diagnosis report shows 3960 strings were scanned and 188 faulted strings were found, with fault rate 4.7%. The top three faults are “PV string open circuit”, “PV module output current abnormal” and “Abnormal curve near MPP in the PV string”.

Smartlogger01 PV string O&M report

1. Information of Task

Task name	CASE2 Plant 49MW	**Creation Time**	2018-12-22 12:17:32
Cleaning status	Uncleaned	**Task type**	PV plant level diagnosis
Total number of strings	392	**Number of faulty strings**	22
Irradiance(W/m²)	967.15(Predictive value)	**Temperature Of Panel(℃)**	64.62(Predictive value)

2. Overview on Diagnosis

NO.	Inverter	Inverter (SN)	String	Voc[V]	Isc[A]	Defective type	Locate	Position of Faulty PV Module
1	10201	XXXXX730246THH900XXX	PV8	-	-	PV string open circuit (PV string breakage/PV string configured by mistake)		
2	11402	XXXXX730246THH900XXX	PV6	802.70	9.37	PV module output current abnormal (shade/glass breakage/hidden crack)		
3			PV8	-	-	PV string open circuit (PV string breakage/PV string configured by mistake)		
4	11801	XXXXX730246THH900XXX	PV3	812.90	8.04	PV module output current abnormal (shade/glass breakage/hidden crack)		
5	10801	XXXXX730246THH901XXX	PV3	806.50	9.01	PV module output current abnormal (shade/glass breakage/hidden crack)		
6			PV7	806.20	9.40	PV module output current abnormal (shade/glass breakage/hidden crack)		
7	10901	XXXXX730246THH901XXX	PV1	805.30	8.94	PV module output current abnormal (shade/glass breakage/hidden crack)		
8			PV2	805.30	8.94	Current mismatch in the PV string (shade/dust/PV module current inconsistent)		
9	10102	XXXXX730246THH901XXX	PV7	-	-	PV string open circuit (PV string breakage/PV string configured by mistake)		
10			PV8	-	-	PV string open circuit (PV string breakage/PV string configured by mistake)		
11	11602	XXXXX730246THH901XXX	PV2	810.80	8.51	Abnormal curve near MPP in the PV string (hotspot/hidden crack/glass breakage)		
12	11901	XXXXXX730246THH901XXX	PV2	821.50	8.59	PV module output current abnormal (shade/glass breakage/hidden crack)		
13			PV3	-	-	PV string open circuit (PV string breakage/PV string configured by mistake)		
14			PV4	811.70	8.83	PV module output current abnormal (shade/glass breakage/hidden crack)		
15			PV5	819.70	8.52	PV module output current abnormal (shade/glass breakage/hidden crack)		
16			PV7	813.10	8.79	PV module output current abnormal (shade/glass breakage/hidden crack)		
17	11601	XXXXX730246THH9020XXX	PV2	807.50	8.72	PV module output current abnormal (shade/glass breakage/hidden crack)		
18			PV3	809.20	8.86	PV module output current abnormal (shade/glass breakage/hidden crack)		
19	12101	XXXXX730246THH901XXX	PV8	-	-	PV string open circuit (PV string breakage/PV string configured by mistake)		
20	12002	XXXXX730246THH901XXX	PV2	782.00	8.65	PV string voltage abnormal (diode short circuit/PV module invalid/PV module quantity incorrect)		
21			PV7	791.50	8.70	PV string voltage abnormal (diode short circuit/PV module invalid/PV module quantity incorrect)		
22	12102	XXXXX730246TJ8900XXX	PV1	820.30	8.78	PV module output current abnormal (shade/glass breakage/hidden crack)		

3. Following advise

NO.	Description	Following advise
1	PV string open circuit (PV string breakage/PV string configured by mistake)	Step 1: Check if the strings are connected correctly, if connections are loose, or not connected. Step 2: If the strings are connected to inverter, then switch off the inverter and pull off the connector between strings and inverter; then measuer Voc of the strings with a multimeter and check whether the Voc is within correct parameters. Step 3: If the Voc is within correct parameters, then check whether the connector between string and inverter is broken, if everthing is ok, then check if there is broken circuit inside of inverter. Step 4: If the Voc is abnormal, then check if there is broken circuit in strings.
2	PV module output current abnormal (shade/glass breakage/hidden crack)	Step 1: Observe the PV string for shade. If there is shade, eliminate the shade and measure again. Step 2: If there is no shadow on panel, check if there are foreign matters or dirt on the surface of the panel, if yes, then measure again after removing the foreign matters. Step 3: If there is no shadow on the surface of panel, please check if there is broken glass, if yes, please measure again after replacing with same model of PV module. Step 4: If no PV module has a broken glass panel, check whether the PV string has been cleaned. If not, clean the PV string and then measure again after the PV module surface is dry. Step 5: If the PV string has been cleaned, scan the PV string using an infrared thermal imager to locate the abnormal PV module. Step 6: If there is no fault, please identify the module with abnormal current by IV tester.
3	Current mismatch in the PV string (shade/dust/PV module current inconsistent)	Step 1: Please check if the scanning is done at a sunny day, current mismatch may occur when the irradiance changes dramatically. Step 2: Check if there is shadow, if yes, please measure again after removing the shadow. Step 3: If no, please check string was cleaned. Step 4: If the PV string has not been cleaned, clean the PV string and then measure again after the PV module surface is dry. Step 5: If string was cleaned, please check if there are panels with low Isc or from other power class by IV testing of each panel.
4	Abnormal curve near MPP in the PV string (hotspot/hidden crack/glass breakage)	Step 1: Please check if the scan was done in a sunny day, the rapid change of irradiance may induce IV curve become abnormal. Step 2: Please check if the string was cleaned. Step 3: If the PV string has not been cleaned, clean the PV string and then measure again after the PV module surface is dry. Step 4: Scan the PV string using an infrared thermal imager to locate the abnormal PV module. Step 5: If no abnormal temperature was found, please use IV test to identify the module with abnormal output current.
5	PV string voltage abnormal (diode short circuit/PV module invalid/PV module quantity incorrect)	Step 1: Check whether the number of PV modules connected to the PV string is correct. Step 2: Observe whether there are traces of burning at the interconnection strip, backsheet, and wiring box. If so, replace the PV module with the same model. Step 3: If none of the above exists, please use IR camera to check if there is short circuited diode or broken ribbon for interconnection. Step 4: If there is no abnormal found on the module with IR camera, please use voltage meter to check the the voltage of the strings (from same MPPT), to see if it is too low. And if yes, please measure the temperature of panels in string to check whether there is abnormal temperature distribution.

01

Figure 4.5 O&M report of the abovementioned PV plant

After reviewing the diagnosis report, one copy of O&M report was taken with O&M engineers to confirm the faults on site.

Following the string number and instruments in O&M, engineers easily found out the faulted string and then verified the faulted module by infrared camera. Figure 4.6 shows three typical examples that were verified after Smart I-V Curve Diagnosis, hotspot, diode short-circuit and shading. These three are all imperceptible faults at DC side but of high risk since the evolution of such faults can lead to the burning of faulted module and maybe spread the fire risk to the neighbored modules and devices. In some accidents we saw in Southeast Asia, the PV plant is built in grass-rich area and the fire starts from one module to a whole plant when it is dry season and the dry grass is not collected in time.

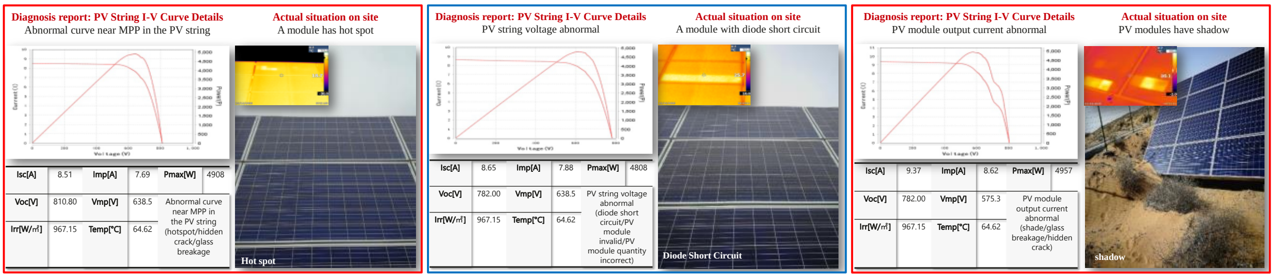


Figure 4.6 Cases of verification of the alarms from Smart I-V Curve Diagnosis

5 Value of Smart I-V Curve Diagnosis

From the above chapters, one can see that Smart IV Curve Diagnosis is one powerful tool to help the plant owner to manage the plant by providing valuable information such as identifying what and where possible problems are occurring at the plant and to provide the necessary steps in confirming the exact root cause of the problem. One key issue is to ascertain the exact value of this tool in order to helps us understand why we need Smart IV Curve Diagnosis and how to make best use of it.

5.1 Secure PV Assets by 100% Inspection

Risk control is the topmost topic for PV plant investment. Each stage has its own risks, which are transferred to O&M after commission. From an ideal concept, the investors and developers should have the capability of accessing all the devices in the PV plant, knowing their state of health.

Unfortunately, in a traditional plant, there are obstacles in front. One is that there is no access of acquiring status of 100% devices from the DC side, which in fact processes the majority of the cost of an entire plant. As mentioned in Chapter 3, traditional inspection methods can only achieve partial inspection so that not all the faults can be detected and then recovered. Moreover, these inspection methods might bring in more risks like labor safety. Under such condition, DC side is not totally transparent and what one knows about the plant is incomplete. But one should make the balance of high cost and asset security when there is no efficient approach of 100% inspection on DC side. As a result, the security of assets is under risk. The other obstacle is about the data collected from the plant even if there are sensors on the DC side. These data are typically lack of accuracy, synchronization, comparability, etc. so that they typically helps little for the investors and developers.

By means of Smart I-V Curve Diagnosis from a 100% sampling perspective, it is possible to evaluate state of health of the entire plant at key stages.

(1) 100% inspection after commission: Quality of the plant and fast defect elimination are two major concerns after commission. Traditional methods have no idea of 100% inspection on the DC side which actually brings risks. Smart I-V Curve Diagnosis helps 100% inspection on the DC side with detailed description on the faults, which provides solid evidence for the investors and developers to recall and solve the problems and thus reduce the risks on the assets.

(2) 100% inspection for O&M: Smart I-V Curve Diagnosis provides string-level inspection for 100% device on the DC side and makes all the devices transparent and traceable to investors and developers, which is definitely helpful for decision making and risk controlling.

(3) Appropriate O&M strategy: whether one fault needs to be recovered is determined by the balance between the value brought by the recovery action and the cost for recovery, indicating that not all the faults are urgent to be recovered. Smart I-V Curve Diagnosis provides the methodology of evaluation of yield loss and system risk for the customers to help them make a right decision with higher ROE.

5.2 Saving Energy Yield Loss by Protecting PV System from Faults

As is described in Chapter 3, any faults in module may lead to the yield loss of energy, most of which can be approximately evaluated by Table 3.3.

Since each plant is independent and the details may vary a lot, it is not easy to evaluate the energy loss at the design stage or before 100% I-V curve inspection. However, a statistical method based on I-V curve data from a large quantity of PV plant may provide a reference value for energy loss.

From 2016-2019, Huawei together with the customers in China led joint innovation projects which have inspected a couple of plants with 1.2 GW capacity in China by means of Smart I-V Curve Diagnosis. These plants cover almost all the regions of China and are commissioned within 5 years. Table 5.1 shows the statistical analysis on all the failures. It can be seen that “PV module output current abnormal”, “Current mismatch in the PV string” and “PV string voltage abnormal” are top three alarms and the possible causes are shade, glass breakage, diode short circuit, etc.

Table 5.1 Statistics on the string faults all over the 1.2 GW PV plants

NO	Item	Failure rate	Weighted factor for one string	Yield loss
1	PV module output current abnormal (shade/glass breakage/hidden crack)	3.30%	5.00%	0.17%
2	Current mismatch in the PV string (shade/dust/PV module current inconsistent)	1.60%	3.00%	0.05%
3	PV string voltage abnormal (diode short circuit/PV module invalid/PV module quantity incorrect)	1.49%	1.80%	0.03%
4	PV string open circuit (PV string breakage/PV string configured by mistake)	1.04%	100.00%	1.04%
5	Slight current mismatch in the PV string (dust/slight shade/glass breakage)	0.95%	1.00%	0.01%
6	Abnormal curve near MPP in the PV string (hotspot/hidden crack/glass breakage)	0.57%	0.00%	0.00%
Total in percentage		8.95%	NA	1.29%

When weighted factors for one string are endowed to specific faults, the approximate yield loss from all faults can be written as:

$$\text{Loss\%}=\sum_{i=1}^{6} P_i * WF_i$$

Where P_i is the possibility of the fault in No i, WF_i is the weighted factor for one string for fault in No i.

As a result, Loss%=1.29% and the approximate economic loss can be written as:

$$\text{Economic Loss}=\sum_{i=1}^{T}\frac{PPA_i*Loss\%*Yield_i}{(1+r)^i}$$

Where PPA_i is the electricity price of year i, T is the total period of electricity purchase, r is the discount rate.

5.3 Saving Time and Cost Compared to Other Approaches

To achieve 100% inspection on the DC side, the only way is traditional I-V testing with 100% sampling. In a 400MWp/300MWac PV plant in the desert of Middle East, this test was mandatorily taken in December, 2019, which is taken in the comparison in this section.

Table 5.2 Comparison between Smart I-V Curve Diagnosis and traditional I-V testing.

For 400MWp	Traditional I-V Testing	Smart I-V Curve Diagnosis
Tools Cost	~$12000-$25000/set * 4 sets (Instruments & software price varies from vendors.)	Only software
Time for Inspection	40 Days	25 Min in total
Time for Analysis	7 Days	
Yields Loss	~200MWh in MEA (Inverter turning off when testing)	Almost 0
Labor	12 extra professionals for testing 2 extra professionals for analysis	Only O&M staff

As is listed in Table 5.2, it can be seen that traditional I-V testing should pay for the tool cost, the man-days for inspection and analysis and the electricity price loss due to yield loss caused by inverter turning off during the testing. For Huawei, Smart I-V Curve Diagnosis needs only one click by O&M staff.

Total cost difference for large scale utility plant should be expressed by the following equation:

$$\Delta Cost=(N*T+(40*12+7*2) * S+Y_{Loss} * PPA)*R$$

Where N the set number of tools, T the price of one set of tool, S salary per man-day for professionals, Y_{Loss} the yield loss during testing, PPA the price for 1kWh electricity generated by PV plant, R the sampling ratio.

Case 1: When it refers to the 400MWp/300MWac ME plant with 100% sampling, ΔCost=$100,400, or ΔCost=$251/MWp, assuming PPA=$0.024/kWh, S=$100/man day.

Case 2: If one 3rd party organization is required to provide the I-V curve testing service, with 30% sampling, ΔCost=$121,260, or ΔCost=$303/MWp, assuming PPA=$0.045/kWh, S=$800/man day and no expense for tools. If 100% inspection is required, ΔCost will increase to ~$900/MWp.

Assuming one I-V inspection per year, ΔCost of the 30-year lifecycle will be ~$12388/MWp with discount rate as 6%.

Two more things must be pointed out are:

(1) Traditional I-V testing has high uncertainty of testing. The synchronization of data is not as good as that from Smart I-V Curve Diagnosis. One major issue is that the soiling level may be different when time elapses, which may lead to the poor comparability of data.

(2) It is required to unplug the strings from inverter before traditional I-V testing, which will probably cause terminal damage and bring in high risk of arc. According to our previous studies, the failure rate of module terminals after unplugging is around 8%, which is 10 times higher than that is as factory.

6 Appendix

6.1 Third-Party Authentications

General Information

制造商：	Huawei Technologies Co., Ltd.
测试项目：	I-V Curve Trace Function Test
测试产品：	Grid-Connected PV Inverter
产品型号：	SUN2000-50KTL
样品序列号：	210107302410G3000009
测试单位：	TÜV Rheinland (Shanghai) Co., Ltd.
报告编号：	15098805 002

Test Result Description:

According to the commission of Huawei Technologies Co, Ltd., TÜV Rheinland (Shanghai) Co., Ltd. Perform the tests on the accuracy of I-V curve trace function of product SUN2000-50KTL and the conclusiton is that the test results fulfill the technical requirements specified by manufacturer.

Tested by：Tobias Yang	Reviewed by：John Dai
Signature：	Signature：
Date：2016.05.03	Date：2016.05.03

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Test Report issued under the responsibility of TÜVRheinland®

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Test Report	
Report Reference No.	15098805 002
Tested by	See cover page
Witnessed by	See cover page
Date of issue	2016.05.03
Total pages of report	20
Testing Laboratory	TÜV Rheinland (Shanghai) Co., Ltd.
Address	No. 177, Lane 777 West Guangzhong Road, Zhabei District, Shanghai, P.R.China
Testing location	TÜV Rheinland (Shanghai) Co., Ltd.
Applicant's name	**Huawei Technologies Co., Ltd.**
Address	Administration Building, Headquarters of Huawei Technologies Co., Ltd., Bantian, Longgang District, Shenzhen, 518129, P.R.C.
Test specification:	
Standard	N/A
Test Report Form No.	I-V Curve Tracer Function Test
Test Report Form Originator	TÜV Rheinland Group
Copyright © TÜV Rheinland LGA Products GmbH Tillystrasse 2 D-90431 Nürnberg, Deutschland. All rights reserved. This report is not valid as a Test Report unless signed by TÜV Rheinland LGA Products GmbH.	
Testing:	
Date of receipt of test items	2016.04.27
Date(s) of performance of tests	2016.04.27
Test item	I-V Curve Trace Function Test
Trade Mark	HUAWEI
Manufacturer	Huawei Technologies Co., Ltd.
Ratings	See model list for detail

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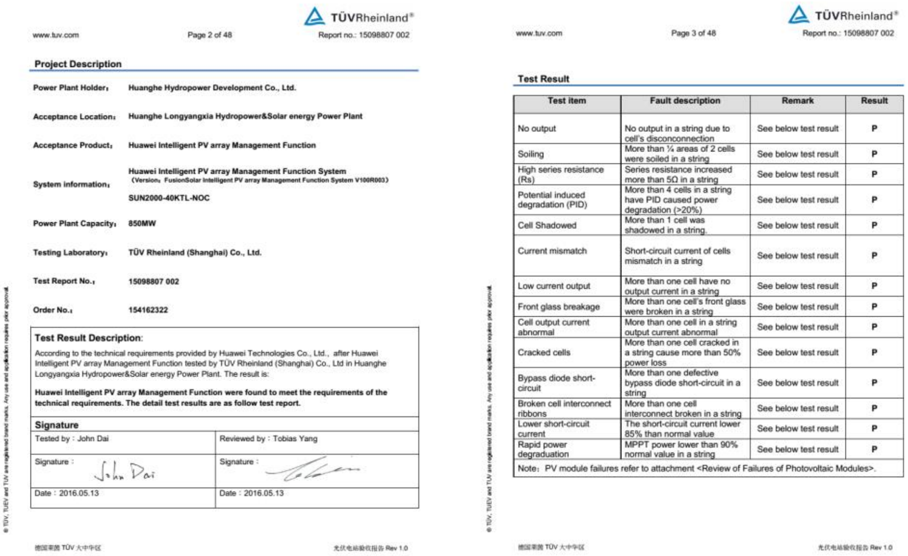
Figure 6.1 Third party's precision authentication report



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Project Description

Power Plant Holder:	**Huanghe Hydropower Development Co., Ltd.**
Acceptance Location:	**Huanghe Longyangxia Hydropower&Solar energy Power Plant**
Acceptance Product:	**Huawei Intelligent PV array Management Function**
System information:	**Huawei Intelligent PV array Management Function System** (Version: FusionSolar Intelligent PV array Management Function System V100R003) **SUN2000-40KTL-NOC**
Power Plant Capacity:	**850MW**
Testing Laboratory:	**TÜV Rheinland (Shanghai) Co., Ltd.**
Test Report No.:	**15098807 002**
Order No.:	**154162322**

Test Result Description:

According to the technical requirements provided by Huawei Technologies Co., Ltd., after Huawei Intelligent PV array Management Function tested by TÜV Rheinland (Shanghai) Co., Ltd in Huanghe Longyangxia Hydropower&Solar energy Power Plant. The result is:

Huawei Intelligent PV array Management Function were found to meet the requirements of the technical requirements. The detail test results are as follow test report.

Signature

Tested by : John Dai	Reviewed by : Tobias Yang
Signature :	Signature :
Date : 2016.05.13	Date : 2016.05.13

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Test Result

Test item	Fault description	Remark	Result
No output	No output in a string due to cell's disconconnection	See below test result	**P**
Soiling	More than ¼ areas of 2 cells were soiled in a string	See below test result	**P**
High series resistance (Rs)	Series resistance increased more than 5Ω in a string	See below test result	**P**
Potential induced degradation (PID)	More than 4 cells in a string have PID caused power degradation (>20%)	See below test result	**P**
Cell Shadowed	More than 1 cell was shadowed in a string.	See below test result	**P**
Current mismatch	Short-circuit current of cells mismatch in a string	See below test result	**P**
Low current output	More than one cell have no output current in a string	See below test result	**P**
Front glass breakage	More than one cell's front glass were broken in a string	See below test result	**P**
Cell output current abnormal	More than one cell in a string output current abnormal	See below test result	**P**
Cracked cells	More than one cell cracked in a string cause more than 50% power loss	See below test result	**P**
Bypass diode short-circuit	More than one defective bypass diode short-circuit in a string	See below test result	**P**
Broken cell interconnect ribbons	More than one cell interconnect broken in a string	See below test result	**P**
Lower short-circuit current	The short-circuit current lower 85% than normal value	See below test result	**P**
Rapid power degraduation	MPPT power lower than 90% normal value in a string	See below test result	**P**

Note: PV module failures refer to attachment <Review of Failures of Photovoltaic Modules>.

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Figure 6.2 Third party's function authentication report