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Fusionsolar

Smart Safety Technology for PV Plants

White Paper

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Contents

01 Background

The PV industry is witnessing unprecedented growth, as the pace to carbon neutrality is accelerating globally and countries are emphasizing energy security and independence. According to the latest report released by the International Renewable Energy Agency (IRENA), the global installed PV capacity reached 1053 GW by the end of 2022. As predicted by the China Photovoltaic Industry Association (CPIA), from 2023 to 2030, the annual installed PV capacity will exceed 90 GW in China and 250 GW in the world. PV power is gradually replacing traditional energy as a primary energy source.

Safety underpins the sustainable development of PV power. The increasing PV module current and the increasing capacity and power of inverters and other key devices, coupled with complex and diversified PV application scenarios, have drawn industry-wide attention on the PV plant safety, which covers electrical safety, grid-connection safety, power supply safety, cyber security, and ecological safety. Among them, electrical safety, which is closely related to personal and property safety, is the top concern and the top priority.Traditionally, PV plant safety design is based on the concepts of "all-round protection", "no blind spots", and "quick response." It focuses on scientific management and timely response. However, the integration of digital technologies and power electronics drives the technical iteration of safety management through digital means.

This white paper comprehensively analyzes PV plant electrical safety issues and accidents, and systematically introduces the latest technologies and practices in the PV plant safety field. It aims to facilitate the application of smart safety technologies for PV plants and promote the rapid and healthy development of the industry.

02 PV Plant Safety Issues and Typical Cases

Among PV plant safety accidents, electrical safety accidents occur most frequently and are the most complex, endangering personnel, equipment, and plants, and therefore calling for joint efforts of the entire industry. From a macro perspective, we need a global view to analyze safety risks of each key node and link end to end. From a micro perspective, we need to locate the root cause of each safety accident and take targeted measures to control risks.

2.1 Overview of PV Plant Electrical Safety Accidents

Electrical safety accidents are caused by various kinds of faults. Any PV module or device and its electrical connection may cause faults and safety accidents of different forms.

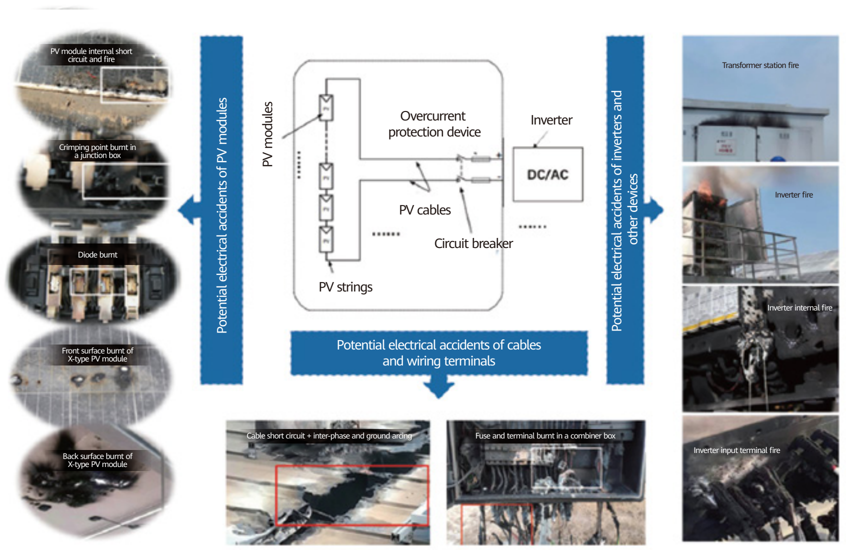

Figure 1 Electrical accidents of PV power systems

2.2 Typical Electrical Faults and Safety Issues of PV Plants

Grounding Fault

At present, grounding faults are the primary causes of plant safety accidents. According to the statistics of a third-party organization, more than half of PV plant fires are caused by grounding faults. In a PV plant, most cables between PV modules, combiner boxes (if any), inverters, and transformer stations are buried underground. These cables and the wiring terminals are prone to damage and contact with the ground. As a result, the insulation of transmission wires to the ground decreases. Once a leakage loop is formed, local heating or electric sparks will be caused, even leading to a fire.

To address grounding faults in PV plants, preventive measures need to be taken. When a grounding fault occurs on the DC side of a PV plant, the inverter should be able to detect the abnormal insulation of the positive or negative terminal and send the fault signal to the monitoring system in the central control room through the communications system deployed in the plant. As the PV inverters connect to an increasing number of DC strings, traditional central inverters and string inverters cannot locate the exact faulty string. Therefore, fault locating requires tremendous manual efforts. In complex scenarios such as deserts, drainage basins, and floating plants, O&M is even more difficult and inefficient.

If a single ground point is faulty on the DC side of a PV plant, the system will not be significantly affected because there is no circuit that forms the grounding current. However, if another ground point is faulty at the same time, the system may be short-circuited, causing device faults and damage and severely affecting the plant safety. To analyze the serious impact of multi-point grounding faults, this white paper focuses on the typical risks and problems of two-point grounding faults.

◎ Ground points on positive terminals

In the following figure, the PV+ terminals of any two PV strings in a central inverter solution are grounded at the same time. This is equivalent to a single-point positive-terminal grounding fault, and the system reports a grounding fault alarm.

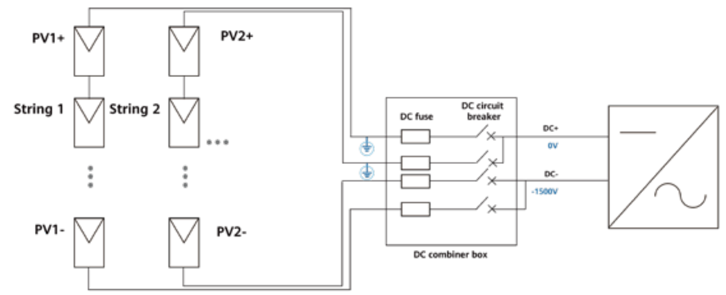

Figure 2 Two PV+ terminals grounded in a central inverter solution

In a string inverter solution, if two ground points occur on PV+ of strings connected to the same inverter, the grounding fault is equivalent to the previous one of the central inverter solution, which is also regarded as a single-point positive-terminal grounding fault. In this case, the system reports a grounding fault alarm.

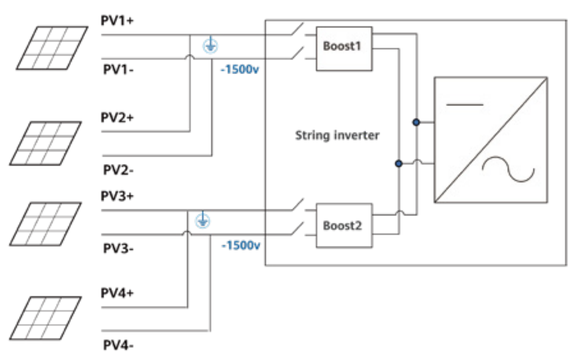

Figure 3 Two PV+ terminals grounded in a string inverter solution

◎ Ground points on negative terminals

In the following figure, the PV– terminals of any two PV strings in a central inverter solution are grounded at the same time. This is equivalent to a single-point negative-terminal grounding fault, and the system reports a grounding fault alarm.

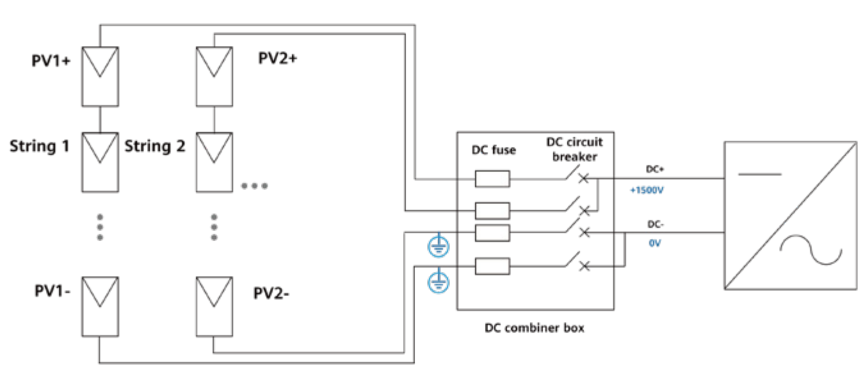

Figure 4 Two PV– terminals grounded in a central inverter solution

In a string inverter solution, if two ground points occur on PV– of strings connected to the same inverter, the grounding fault is equivalent to the previous one of the central inverter solution, which is also regarded as a single-point negative-terminal grounding fault. In this case, the system reports a grounding fault alarm.

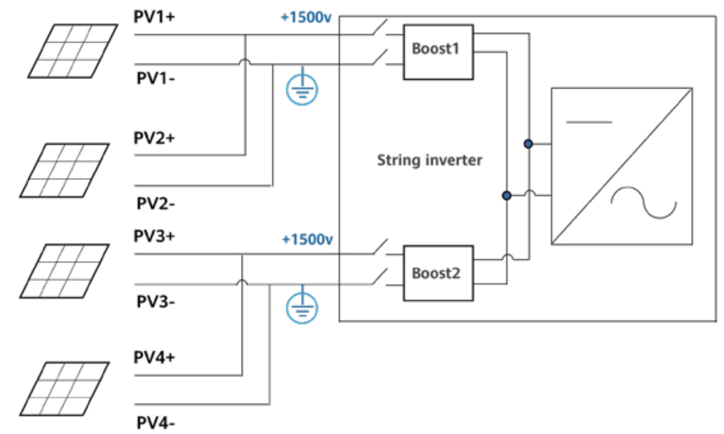

Figure 5 Two PV– terminals grounded in a string inverter solution

If the neutral (N) wire of a non-electrically isolated inverter is grounded (for example, TN-C), the power module in the inverter may be short-circuited and fails, as shown in the following figure.

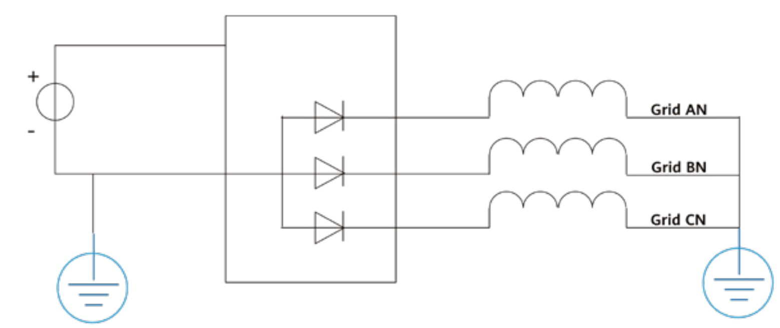

Figure 6 N wire grounded, causing a short circuit

◎ Ground points on positive and negative terminals

In the central inverter solution, if PV+ and PV– of any PV string are grounded at the same time, it is equivalent to a PV string short circuit. Generally, the short-circuit current of a PV string is 1.1 times the peak current. Therefore, it is difficult for the fuse to effectively interrupt the current when a short circuit or overcurrent fault occurs on the DC side.

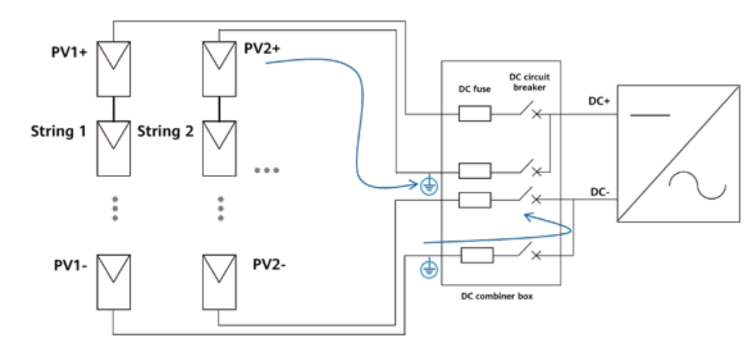

Figure 7 Positive and negative terminals grounded in a central inverter solution

In the string inverter solution, if both PV+ and PV– under the same BOOST circuit are grounded, the grounding fault is equivalent to that of the central inverter solution. If PV+ and PV– of different BOOST circuits connected to the same inverter are grounded, the inverter may experience a high voltage of 3000 V and be damaged.

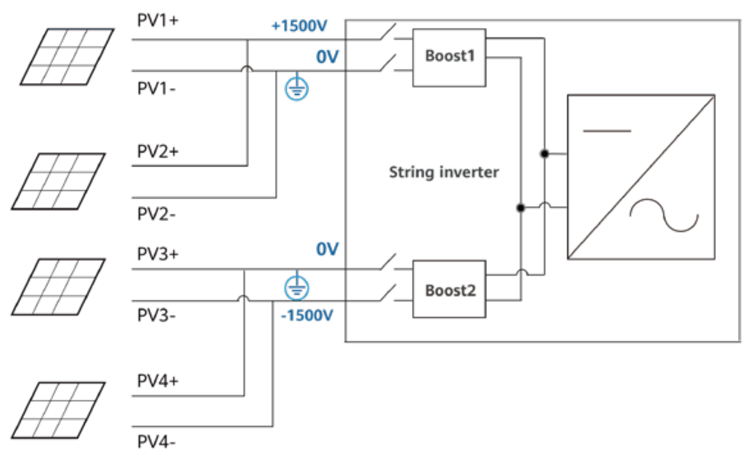

Figure 8 Positive and negative terminals grounded in a string inverter solution

When the BOOST circuit is designed in a symmetric topology (as shown in the following figure), PV– and BUS– are not directly connected. If the positive and negative terminals are grounded, a high voltage of 3000 V occurs. This circuit architecture does not pose high requirements on the control algorithm. However, in rainy and snowy days, if water or snow accumulates, the inverter may be damaged due to poor contact or cable damage.

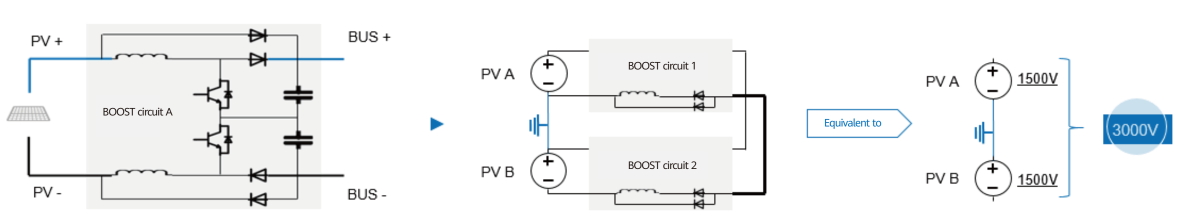

Figure 9 Symmetrical BOOST topology; PV+/PV– multi-point grounding, causing a high voltage of 3000 V

The following figure shows the BOOST circuit topology design of a flying capacitor. In this circuit architecture, PV– is directly connected to BUS–, which effectively avoids inverter overvoltage caused by multi-point grounding. However, this mode has higher requirements on the inverter control algorithm, and is difficult to implement.

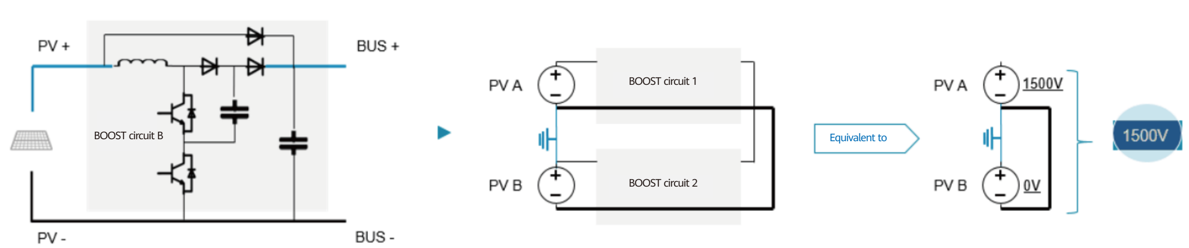

Figure 10 Flying BOOST topology to avoid multi-point grounding and overvoltage

Electrical Insulation Fault

Insulation faults are major causes of electrical safety risks. Electric field, thermal, and chemical factors can deteriorate the performance of insulation materials and lead to insulation failure. The main form of insulation failure is insulation breakdown. When the electric field strength applied to the dielectric is higher than the critical value or under a certain electric field strength, the insulation resistance of the dielectric is lower than the critical value. As a result, the current passing through the dielectric surges, causing insulation failure. This phenomenon is also called dielectric breakdown, which can lead to serious consequences such as fire.

Generally, the IP rating of a traditional central inverter is IP54, and that of a traditional string inverter is IP65. During operation or O&M, water vapor, dust, and salt fog may enter an inverter to reduce the creepage distance. As a result, the insulation of inverter boards or modules deteriorates greatly, causing insulation failure or overheating and then sparks that can burn the entire inverter.

Condensation caused by water vapor is one of the most common insulation failure reasons of PV plants. To avoid inconsistent air pressure inside and outside the compartment caused by temperature rise during operation, an inverter is equipped with a ventilation valve, which can resist water but not water vapor. Water vapor will be generated on the internal components of the inverter as it is running in the daytime and the rising temperature will increase the internal pressure to vaporize water. When the night comes, the inverter stops running as solar irradiance declines, and the temperature in the compartment decreases. If it reaches the dew point, condensation occurs in the inverter compartment, resulting in insulation faults of components and then safety risks.

Figure 11 Fire caused by inverter insulation failure

DC Reverse Connection

A PV plant involves many long cables. During cable connection, the male and female connectors may be reversely connected, causing the DC reverse connection fault. Traditionally, when multiple strings are connected in parallel, fuses are used for overcurrent protection. If one PV string is reversely connected, the voltage of the faulty circuit may be twice the voltage of the PV string. The existing 1500 V fuse may not reliably interrupt the current, causing blowout and fire.

The following figures show the high voltage caused by DC reverse connection in a PV string in the traditional central inverter and string inverter solutions.

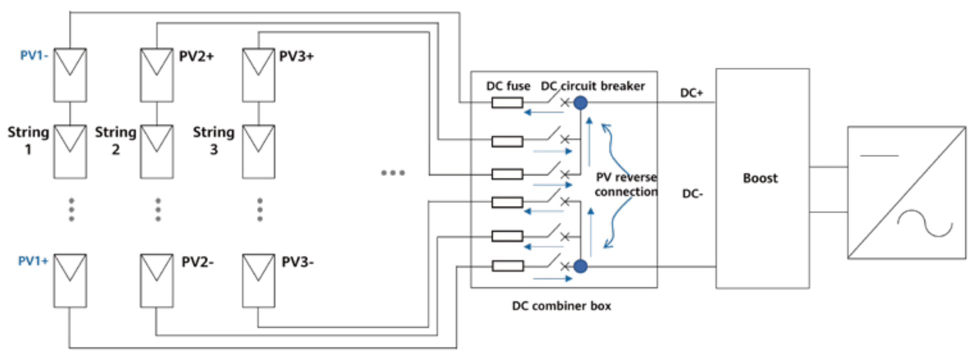

Figure 12 DC reverse connection in a central inverter solution, causing a high voltage of 3000 V that exceeds the fuse breaking capacity

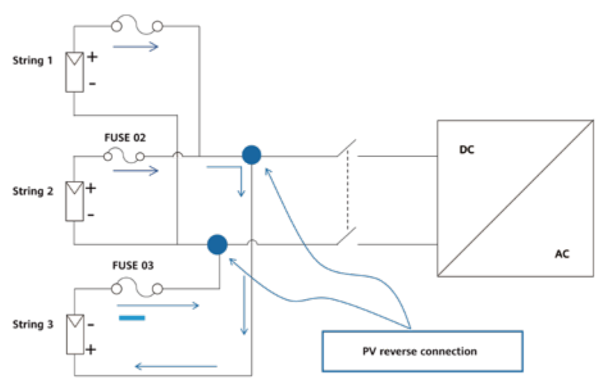

Figure 13 DC reverse connection in a traditional string inverter solution, causing a high voltage of 3000 V that exceeds the fuse breaking capacity

If all PV strings in the inverter or BOOST circuit are reversely connected, the diode in the device is equivalently a short circuit and may be burnt, as shown in the following figure.

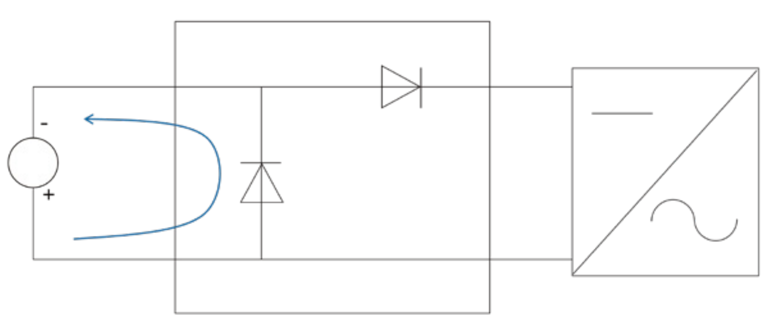

Figure 14 All PV strings reversely connected and diode short-circuited

DC/AC Terminal Contact Fault

A PV plant involves a large number of terminal connections. For example, a 100 MW plant can have more than 7000 PV strings that need to be connected through more than 14,000 DC terminals. And faults caused by poor terminal contact are also common plant safety problems. The possible causes are as follows: During terminal production, the metal core is not properly crimped; during plant construction, the terminal is not properly connected due to improper operations; during plant operation, external forces generate stress between terminal contact points. As a result, terminals are loosely connected. The following figures show cases of contact deterioration due to long-term impact of strong winds and land subsidence.

Figure 15 Poor contact of terminals due to land subsidence

Poor contact of terminals directly causes terminal overtemperature. However, because the temperature of an inverter DC terminal cannot be detected, the fault may be escalated to DC arcing and even fire.

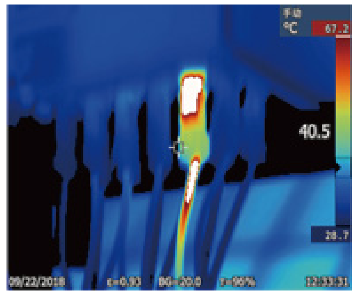

Figure 16 Overtemperature due to a terminal fault

Figure 17 Fire caused by terminal overtemperature

DC Fuse or Combiner Box Fault

Due to the insufficient standards for DC overcurrent protection of PV systems, only IEC 62548 *Photovoltaic (PV) arrays – Design requirements* is used as the main basis. In engineering application, defects exist in phases such as the selection of overcurrent protection devices and the quality control of fuses and circuit breakers. In central inverter solutions, fuses are usually used for overcurrent protection at the module level, string level, and combiner box level. Due to unmatched model selection, disconnection protection failures often occur at the early stage of a project. In addition, the short-circuit current on the DC side comes from PV strings, which is only 1.1 times the peak current of PV modules. Therefore, when a short circuit or overcurrent fault occurs on the DC side, it is difficult for the fuse to effectively interrupt the current. In traditional string inverter solutions, there is no active disconnector on the DC side. When a short circuit occurs inside the inverter, the faulty circuit cannot be disconnected, increasing fire risks on devices such as inverters and combiner boxes.

Figure 18 Inverters and combiner boxes on fire due to DC short circuits

DC Arc Fault

A PV system is built upon numerous terminals on the DC side where arcs are likely to be generated due to various reasons, such as loose terminals, poor contact, cable disconnection, aging, carbonized, or damaged insulation materials, and damp or corrosive wires.

Among the three major types of arcs, including series arc, parallel arc, and ground arc, serial arc is the most common one in arcing accidents, accounting for 80%.

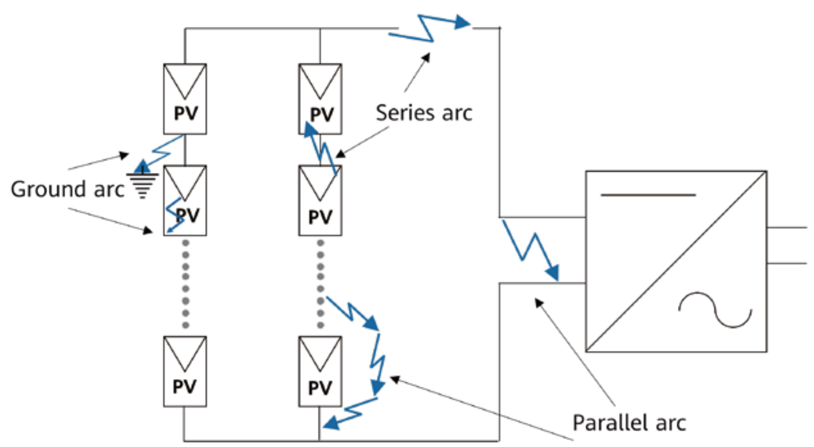

Figure 19 Common arc faults

Inverter Internal Fault

If the capacitor or IGBT inside an inverter fails, a bus or half-bus short circuit may occur. The relay and transformer station MCCB on the AC side can effectively disconnect the faulty circuit. However, the DC side lacks the circuit disconnection capability. If a fault inside the inverter causes a breakdown, the current on the AC side will reversely flow into the DC side. In such cases, a central inverter cannot effectively interrupt the current on the DC side. A traditional string inverter usually uses switches for protection and does not support active disconnection, therefore being unable to stop the spread of an internal fault.

Especially, PV modules are moving toward high power and high current, and the inverter power or the number of PV strings corresponding to a combiner box keeps increasing. Therefore, the energy during backfeeding also increases, posing higher safety risks across the link from PV modules, cables, to inverters.

Arcs in the Low-Voltage Cabinets of Transformer Stations

An arc is an ionized high-temperature gas flow. At the early stage of arc ignition, shock waves generated by air deflagration and subsequent high-temperature air flows can greatly harm human bodies and devices. The protection for the PV plant AC side is relatively mature, with complete standards available. However, when a circuit breaker disconnects the faulty circuit, arcs and insulation breakdown on the low-voltage side still occur, resulting in safety risks and even safety accidents.

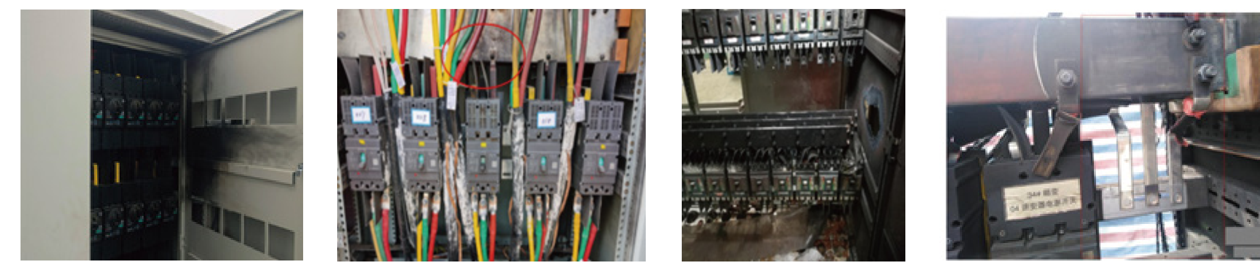

Figure 20 Safety accidents caused by arcing at a transformer station

When the MCCB of a transformer station performs disconnection, the low-voltage cabinet of the transformer station may be faulty or severely damaged. According to the joint analysis of historical onsite cases, the fault path is as follows:

- In a PV plant, the short-circuit current on the low-voltage side of the transformer station is high and may reach 25 kA or even 30 kA, depending on the transformer capacity and line impedance.
- When a common 800 V MCCB acts in response to a short circuit fault, some high-temperature charged ions or particles are ejected.
- The ejected ions and particles directly fall onto the positions near the upper and lower parts of the switches. When components such as exposed conductive copper bars exist near the switches of the low-voltage cabinet, the high-temperature conductive particles greatly reduce the air insulation capability between the exposed copper bars and cause insulation breakdown, short-circuiting the branch busbar or main busbar.
- The busbar short circuit causes the internal discharge and fault to spread.

03 PV Plant Smart Safety

3/1 Smart Safety Design Concept: Self-Sensing, Self-Diagnosis, Self-Control, and High Protection Level

To ensure PV power safety, we should first ensure that the plant equipment and system integration meet the requirements of safe operation of a plant. More importantly, they must meet the O&M requirements of long-term plant operation with few or no engineers attending.

As mentioned above, electrical safety accidents are caused by various kinds of faults. From the perspective of O&M, to prevent accidents, we need all-round monitoring and quick and accurate response, which are difficult to be implemented in traditional safety design. Therefore, digital technologies and other intelligent means are required to improve PV power safety technology and meet the preceding requirements. According to the No. [2022] 39 of the State Council, five departments, including the Ministry of Industry and Information Technology (MIIT), jointly issued *Smart PV Industry Innovation and Development Action Plan (2021-2025)*. Figure 21 shows an example of smart safety of PV plants according to the preceding requirements.

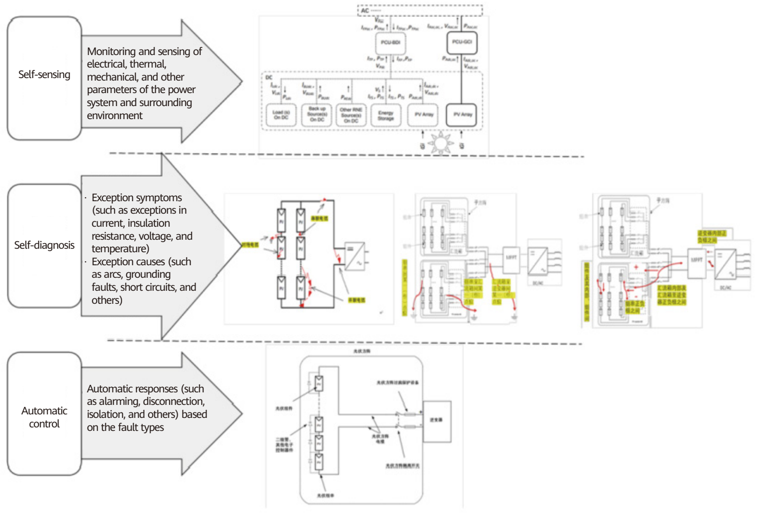

Figure 21 PV plant smart safety

3/2 Design Framework and Technology for PV Plant Electrical Safety (Comprehensive I/V/R/T Diagnosis)

Digitalization is the basis of intelligent diagnosis and control. Traditionally, inverters detect current and voltage (IV) at the string level. Now, based on the latest-generation design concept, Huawei uses digital technologies to diagnose the current (I), voltage (V), resistance (R), and temperature (T).

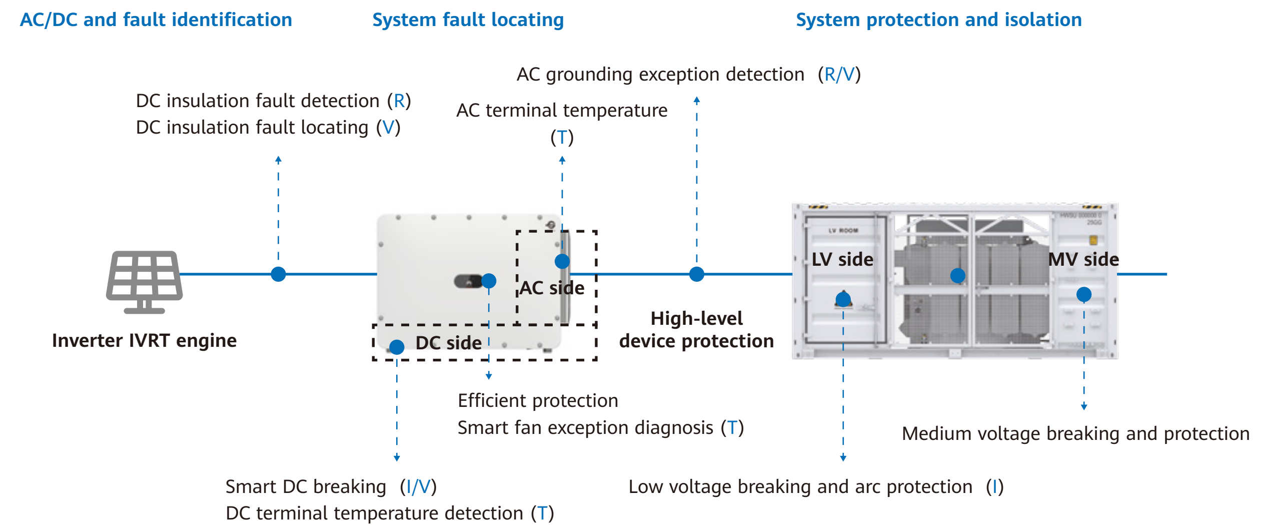

Figure 22 Comprehensive I/V/R/T diagnosis

DC Side: MPPT-level DC Insulation Diagnosis

Ground insulation failure is a common fault in a PV plant, especially in damp areas such as sea surfaces and drainage basins. According to section 7.10.1 in the NB 32004 standard, an inverter connected to an ungrounded PV array must measure the insulation resistance between the PV array input and the ground before the system is started. If the impedance is less than Umaxpv/30 mA (Umaxpv is the maximum output voltage of a PV array), the inverter must report an alarm. If the inverter is not electrically isolated, it cannot be connected to the grid.

Before the system is started, inverters in the plant test whether the ground insulation meets the requirement. If an insulation fault occurs, the corresponding inverter reports an alarm and can be located. However, inverters cannot determine the specific fault point. Therefore, the subsequent fault locating needs to be performed manually. However, the increasing power of PV inverters and increasing number of PV strings make troubleshooting much more difficult and time-consuming.

Huawei's MPPT-level DC insulation diagnosis technology enables inverters to scan the insulation of each MPPT circuit. In this way, the MPPT circuit corresponding to an insulation fault can be accurately located, greatly improving the fault location accuracy. If the fault occurs on a single point, the faulty PV module in the PV string can be located through intelligent detection of voltage change, greatly shortening the fault locating time.

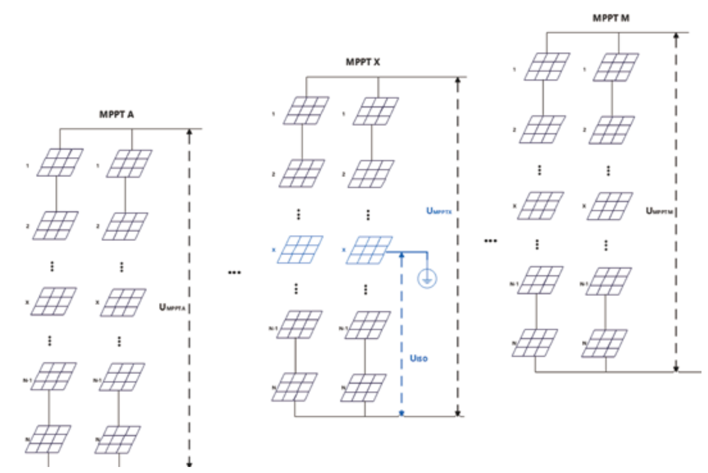

Figure 23 MPPT-level DC insulation diagnosis precision diagram

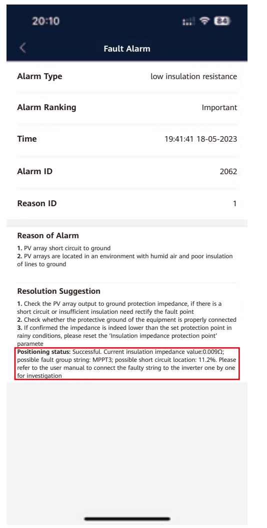

Figure 24 Insulation detection fault alarm

DC Side: Smart String-Level Disconnect

Huawei's Smart String-Level Disconnect technology (SSLD-TECH) implements active disconnection on the DC side and precise string-level protection. The SSLD-TECH consists of three parts: inverter detection and logic judgment system, tripping control system, and trippable DC switch system. Based on traditional switches, the trippable DC switch system adds the energy storage module, control command interface, status feedback interface, reset button, and the innovative electronic release (generally, the electromagnetic release and thermal release are used for overcurrent protection). This technology can accurately capture slight changes of parameters such as the current and voltage. Based on a complete set of logic and algorithms, it can effectively identify multiple faults.

- Reverse PV string connection: After the switch is turned on, the reversely connected PV string forms a loop with other branches of the corresponding MPPT circuit. The input voltage of the PV string is close to 0 while the input current is reverse, which is the short-circuit current of the PV string under the current irradiance. After determining that the PV string is reversely connected based on electrical parameters, the inverter sends a disconnection command.
- Backfeeding: When the PV string voltage in one branch of the MPPT circuit exceeds the open-circuit voltage of the PV string in the other branch, backfeeding occurs on the PV string. The inverter makes a logic judgment based on the electrical parameters, and then sends a disconnection command.
- Bus short circuit: When the DC bus/half-bus voltage quickly drops from the normal value to the critical value, the inverter identifies the bus short circuit fault and immediately sends a disconnection command to interrupt all DC currents.

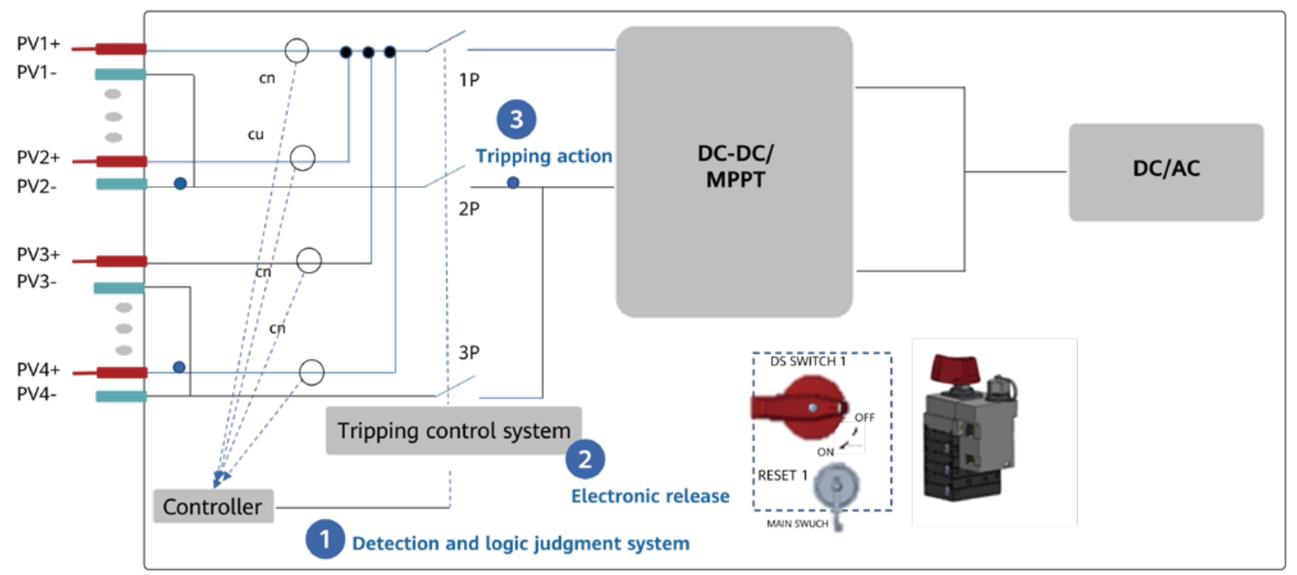

Figure 25 SSLD diagram

DC Side: DC Arc Protection

The existing DC arc detection technology in the industry mainly uses an arc current/voltage frequency domain, including characteristics information such as the frequency, energy, and variation, to detect DC arcs. An integrated algorithm package is provided to debug different threshold parameters. The following two difficulties need to be resolved:

One is noise adaptability. The onsite running environment of equipment is complex. The arc detection algorithm and threshold setting in conventional solutions are mainly based on human experience. When the environmental noise is close to the arc spectrum characteristics, the arcs cannot be effectively distinguished, which may cause false protection. In addition, in parallel and ground arc detection, the noise floor varies in different environments. The current technology cannot effectively identify the arcs.

The other is scenario adaptability. As the current of PV modules and the power of a single inverter increase continuously, the length of input cables and the maximum arc current may exceed those in standard test conditions. With the increase of current and cable length, the characteristic signal of arcs gradually weakens, which raises higher requirements for the precision of detection instruments and algorithms.

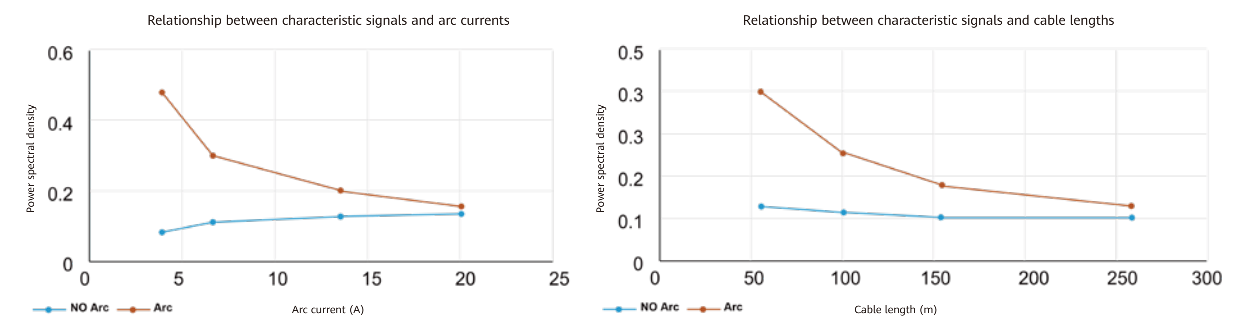

Figure 26 Relationship between arc characteristic signals and arc currents/cable lengths

To address the preceding difficulties, Huawei combines AFCI with deep learning technologies based on its accumulated technical experience in ICT and intelligence fields to launch the smart AFCI solution. This solution has been widely used in distributed scenarios. It supports a maximum input cable length of 200 m and rapid shutdown within 0.5s. In 2020, this solution has obtained the highest L4 certification issued by CGC. Huawei plans to launch a DC arc detection solution for utility-scale PV plants.

DC Side and AC Side: Smart Terminal Detection

In traditional solutions, the DC terminals of inverters are fixed on external mechanical parts. The terminals are routed through cable harnesses, pass through DC switches, and then reach PCBs. This solution is relatively simple in design. However, on one hand, DC terminals need to be perforated, positioned, and secured one by one, and pins need to be manually inserted after the insulation parts are fixed, resulting in low efficiency and easily causing improper insertion. On the other hand, once the temperature of an abnormal point increases due to external factors such as loose connection and damage, the inverter can detect the electrical signal and identify the exception only after the electrical signal is affected because the cable is burnt by the high temperature. But it is too late. In addition, because a large number of cables are connected, the fault is more likely to spread.

To avoid these problems, Huawei innovatively adopts the on-board terminal design. Customized on-board terminals can be directly soldered on PCBs through wave soldering, eliminating the need for manual pin insertion and cable routing. This reduces the risk of poor DC terminal connection caused by improper routing, ensuring high reliability in production. After the terminals are installed on the boards, NTC sensors can be added near the through-current points of the terminals. In this way, data can be collected, which is the prerequisite for digital and intelligent terminal detection. Then, the collected data is transmitted through the signal links on the PCBs, and signal detection and data calculation are performed by chips to finish intelligent terminal detection. Especially, when the temperature of DC terminals is abnormal because terminals are not properly connected, metal cores are not properly crimped, terminals are in poor contact due to external forces, or chemical contamination is caused, the system can quickly report the fault in real time and start protection to prevent the fault from deteriorating and spreading.

Figure 27 Smart terminal detection flowchart

Transformer Station Side: Low-Voltage Electrical Selection and Protection Design

Fault isolation and protection must be provided during the design of the low-voltage cabinet of a transformer station. For example, when an MCCB acts in response to a short circuit at the lower level, other low-voltage branches or the low-voltage main bus should not be affected due to arcing.

To solve the preceding issue, in its new version of solution, Huawei optimizes the transformer station design as follows:

- Arc chutes with deionization grids are added to MCCBs to extinguish arcs by reducing the arc temperature and reduce the conductive particles ejected from the MCCBs.
- According to GB 7251-12-2013 *Low-voltage switchgear and controlgear assemblies — Part 2: Power switchgear and controlgear assemblies*, the low-voltage cabinet must implement internal isolation of Form 2b or higher (the functional units and cable inlet terminals are isolated from the main bus), or insulate the main busbar and branch busbars.

In this way, even if conductive particles are ejected from MCCBs, the MCCBs will not cause insulation breakdown between different phases of the busbars, thereby avoiding fault spreading.

Figure 28 Insulation protection solution for branch buses of low-voltage cabinets

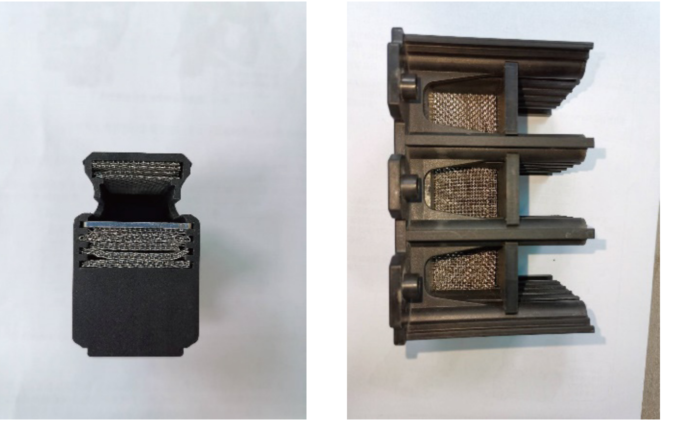

Figure 29 MCCB arc chutes with deionization grids

Entire System: Efficient Protection, Corrosion and Dust Resistance

Currently, the construction of clean energy bases in China covers multiple typical scenarios, such as deserts, drainage basins, plateaus, and offshore PV plants. PV system devices also face challenges in harsh environments, such as high temperature, high humidity, strong sandstorm, high altitude, and high salt fog. Therefore, the structure reliability design of inverters is crucial. Huawei's latest 300KTL Smart PV Controllers adopt multi-level structure safety design.

- IP66 dustproof and waterproof: The inverters are protected from damage even when they are impacted by strong waves or strong water spray. To reduce splicing gaps, Huawei Smart PV Controllers use rust-proof aluminum plates and separate power compartments from maintenance compartments to ensure high reliability.
- C5-M anti-corrosion: Huawei Smart PV Controllers have passed strict salt spray and condensation tests where coastal high salt spray scenarios are simulated. At 40°C and 93% RH, salt spray is performed to simulate industrial areas in high humidity and harsh atmosphere environments.
- Automatic dust removal design: In deserts, there is much dust and sand. The air filters of inverter fans are easily blocked by dust, which affects heat dissipation and causes the inverters to run in derating mode. Huawei Smart PV Controllers use IP68-rated fans, which can rotate forward and backward through intelligent control. During normal operation, the fans rotate forward for ventilation and heat dissipation. In the morning and evening, based on the power, the inverters automatically enable the fans to rotate reversely to blow out blockages such as dust, greatly improving O&M efficiency and avoiding energy yield loss.

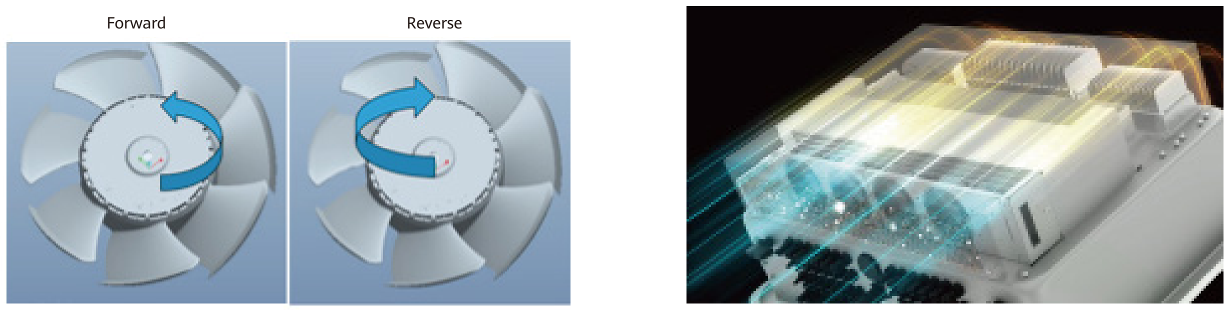

Figure 29 Diagram of smart fan dust removal

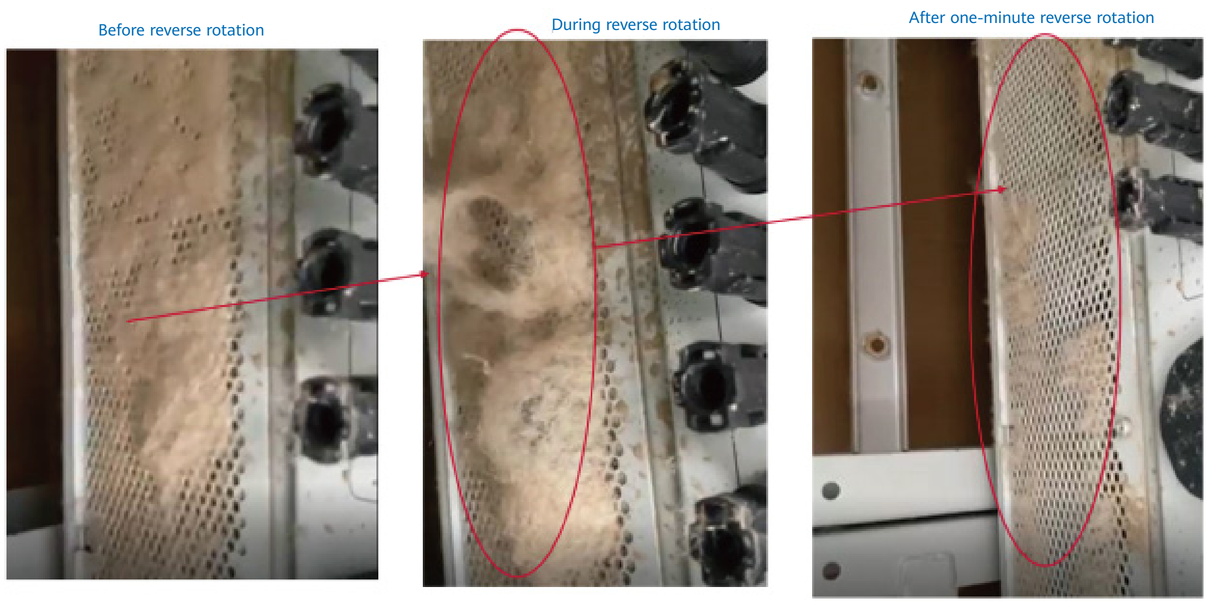

Figure 30 Effect of smart fan dust removal

04 Summary

Centered on data and supported by technologies such as communication networks, data processing, and intelligent diagnosis, digital and intelligent transformation of the PV industry is inevitable. Using digital technologies to reconstruct the safety design of PV power and achieve active safety is an inherent requirement for the healthy development of the industry.

Currently, technologies related to smart safety of PV power have been preliminarily applied. Huawei's leading technologies related to smart safety, such as SSLD, smart DC arc detection, and Smart I-V Curve Diagnosis, have been recognized and applied in the industry.

Focusing on the requirements of "self-sensing, self-diagnosis, self-maintenance, and self-control", there is still a long way to develop and apply smart safety technologies.

In the future, industry players need to collaborate to perform top-level design of smart safety systems, carry out basic research, and develop and apply underlying technologies. In this way, we can jointly build high-quality PV plants and accelerate PV power to become the main energy source of high quality, eventually realizing carbon neutrality.