Arc Fault Circuit Interrupter (AFCI) for PV System Solutions White Paper

2025

Introduction

Globally, the energy crisis, the sense of urgency regarding climate change and the goal of carbon neutrality have driven a new round of energy revolution. Relying on the Chinese "3060 Goals" (Carbon Peak by 2030 and Carbon Neutrality by 2060), various countries have formulated new energy strategies. Photovoltaic power generation, as a clean, efficient, easily deployable and technologically mature energy form, has rapidly risen and become the main force in the development of new energy. According to the prediction of the International Energy Agency (IEA), by 2050, 75% of global energy consumption will come from clean energy, and the proportion of PV power generation will exceed 30%.

The rapid development of the PV industry undoubtedly accelerates the pace of energy transition, but at the same time, it also poses new challenges to the safety of PV systems. Among them, the DC arc problem of the PV system has become a key technical challenge affecting the stable operation of the system.

In response to the complexity and urgency of the DC arc issue, the compilation of this white paper aims to comprehensively sort out and introduce the current status, development trends, and practical solutions of photovoltaic DC arc detection and protection

technologies. Its goal is to promote widespread cognition of industry and facilitate technological progress, and provide professional support for the high-quality development of the PV industry.

This white paper further elaborates on the significant role of DC arc detection and protection technology in ensuring the long-term reliable operation of PV power stations and guaranteeing the overall safety of the system. It also helps to promote the establishment of an industry standard system, supporting the sustainable and standardized development of the PV industry in the future. Under the "dual carbon" goal, this is not only an inevitable requirement for improving the technical level of PV power generation systems, but also a fundamental guarantee supporting the development of global green energy. The release of the white paper will provide guidance for the photovoltaic development and safe operation of the entire industry, and at the same time, lay a technical foundation for achieving safe, reliable and efficient clean energy development. It has a great significance for the green transformation of energy in China and even the world.

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Current situation and trend of photovoltaic industry

1.1 Energy crisis, the increasing penetration rate of Solar power, the danger of DC high voltage and the harm of arc faults

Under the strong impetus of the "dual carbon" goal, the process of the global energy structure's transformation towards low-carbon is continuously accelerating. As a pillar of clean energy, PV power generation is experiencing an unprecedented explosive growth. In recent years, the global installed capacity of photovoltaic power has shown a steady upward trend. According to statistics, the global photovoltaic market's newly installed capacity reached as high as 495GW in 2024, representing a year-on-year growth of 14%. Moreover, it is expected that the average annual growth rate of the global photovoltaic newly installed capacity will remain above 20% in the next five years. In terms of regional distribution, the European Union added 66GW of photovoltaic installed capacity in 2024, PV power generation has become the most rapid growth power generation in the energy sector in local, increasing by 22% compared to 2023. As a leader in the global PV industry chain, China's development in PV industry is unstoppable. It not only holds a dominant position in the production end, but also leads far ahead in the application end. In 2024, China's newly added photovoltaic installed capacity is approximately 277GW, accounting for more than half of the global total. Centralized and distributed PV systems are advancing in parallel, jointly promoting the vigorous development of China's PV industry.

However, the rapid expansion of photovoltaic installed capacity has also brought a series of safety challenges, especially the issue of DC arc, which is becoming increasingly prominent. Unlike AC systems, photovoltaic DC systems have non-zero crossing characteristics due to the use of high-voltage DC structures, which means that once an arc is formed, it is difficult to extinguish naturally. DC arc faults are prone to occur in situations such as loose wiring, aging equipment, improper construction, or insulation failures. Once an arc fault occurs, it may cause sustained local high temperatures, and in severe cases, even lead to a fire. Even more tricky is that DC arcs are often highly concealed, and traditional safety devices are difficult to detect and block in a timely manner, posing a significant challenge to the energy efficiency improvement and operation safety of PV systems.

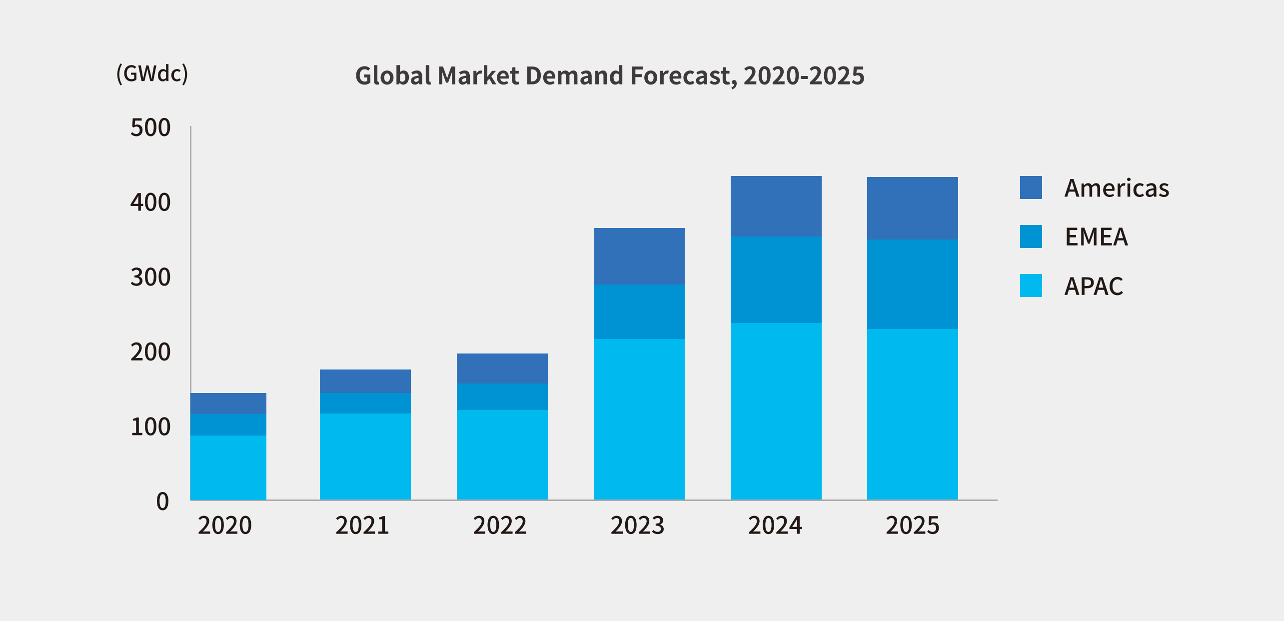


Figure 1: Global Market Demand Forecast, 2020–2025. Source: Wood Mackenzie

1.2 Analysis of DC arc risk in different PV power generation scenarios

The application scenarios of PV power stations are rich and diverse, and different types of PV systems have differences in installation forms, environmental conditions, and operating scales, which makes them face unique challenges in DC arc detection and protection.

In residential photovoltaic scenarios, the system capacity is relatively small, but the equipment nodes are scattered, the wiring is concealed, and it is usually installed near the roof of buildings or combustible materials, so the risk of fire caused by electric arcs is more prominent. In 2022, a typical accident occurred in a province in China where a residential PV system suffered from poor contact due to aging connectors, ultimately leading to arcing and causing a roof fire. The on-site losses were severe. Such incidents undoubtedly sound the alarm for the industry and highlight the urgent need for technical protection of residential PV systems.

The DC side of a string inverter consists of a PV array, a bridge structure, and the inverter itself. Series arcs can occur at any position in the circuit, while parallel arcs primarily appear within the bridge structure. Once a parallel arc occurs, additional protective equipment is often required to address the issue due to its difficulty in extinguishing.

Figure 2: Actual Scene Photo of a Photovoltaic Fire

In the industrial and commercial photovoltaic scenarios, due to their larger installed capacity and greater number of units, the DC side wiring is more complex, and they are usually concentrated in areas such as factory rooftops. The large fluctuations in power consumption and the long-distance laying of cables make the arc hazard more prominent. For instance, during the operation of a certain industrial PV power station, an arc spread due to a transmission line fault and affected other systems, causing local production to be interrupted for several hours and resulting in incalculable economic losses.

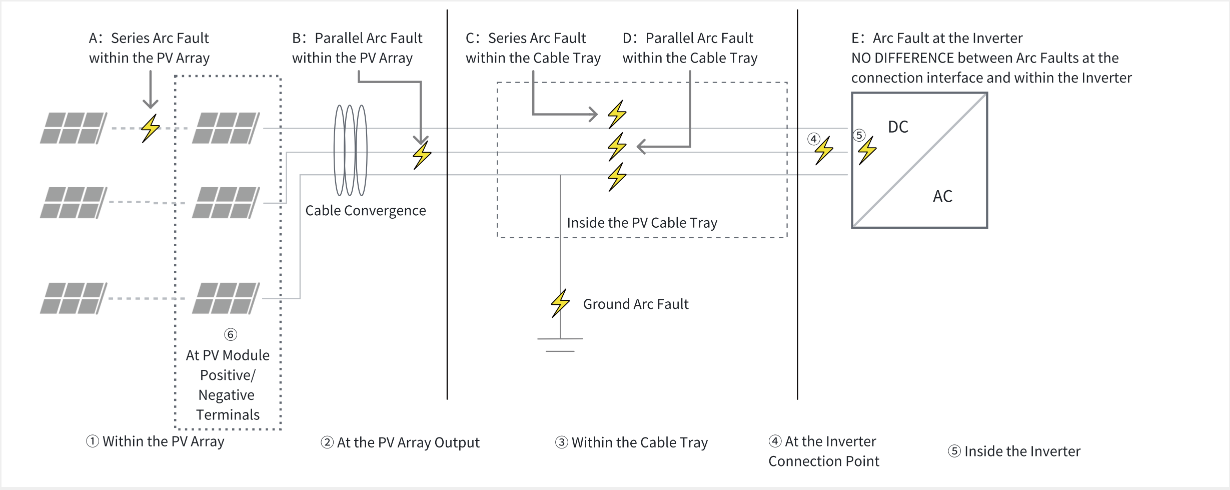


Figure 3: String inverter application

Large ground-mounted power stations, with their massive system scales, single-circuit DC cables potentially reaching tens of kilometers in length, complex wiring, and harsh operating environments, impose stricter requirements for arc detection and rapid response capabilities. In remote regions with extreme cold or heat, long-term environmental stress can lead to a decline in the insulation performance of module, increasing the likelihood of arcs. For instance, a large PV power station in a western region experienced a circuit interruption lasting eight hours during its initial operation due to an arc caused by a tail line fault in the terminal module, significantly impacting overall power generation.

The DC side of a centralized inverter includes PV arrays, combiner boxes, busbars after combiner, and inverters. In high-current scenarios, the current difference before and after convergence is significant, which poses higher requirements for arc detection. It is recommended to adopt a separate detection method.

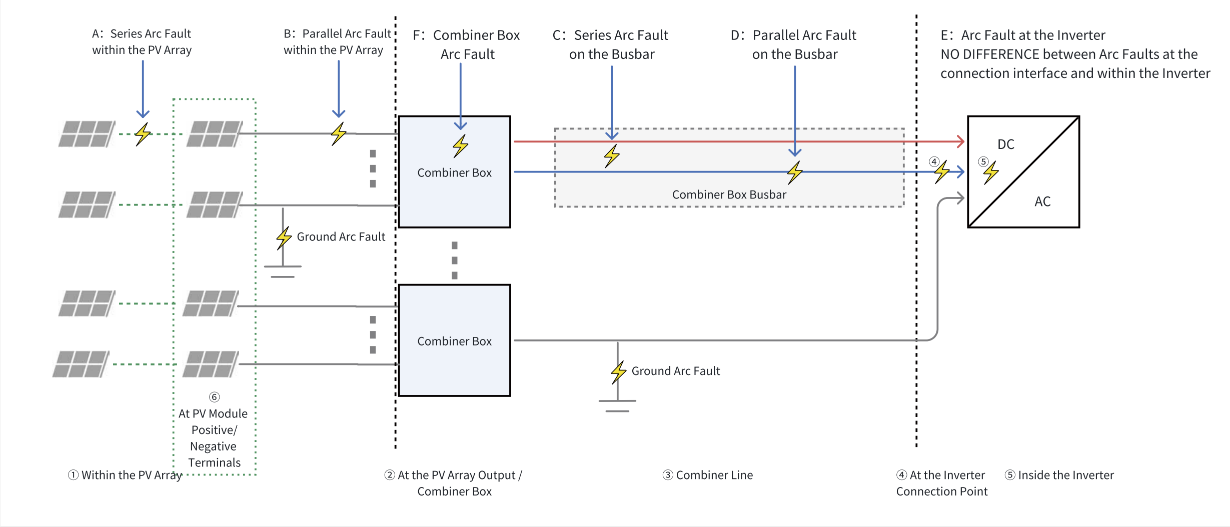


Figure 4: Centralized inverter application

Through the analysis of the above different scenarios, we can clearly see that the DC arc problem is a major risk jointly faced by household, industrial and commercial, and centralized photovoltaic application scenarios. However, its specific manifestations and the consequences it causes show significantly differentiated characteristics in different scenarios. Therefore, tailoring more targeted technical solutions for each type of photovoltaic scenario has become the key for the current industry to overcome this challenge.

1.3 Summary of Requirements for PV DC Arc Fault Protection and Rapid Shutdown Across Different Countries and Regions

As the large-scale advancement of global PV power generation projects, the issue of DC arc is no longer just a concern for the industry; it has also become a mandatory regulation in photovoltaic design, operation and supervision. Internationally, advanced countries and regions have successively introduced a number of regulations and standards, putting forward clear requirements for the safety of PV systems.

The United States is a pioneer in the application of photovoltaic DC arc fault protection.According to the National Electrical Code of the United States (NEC 2023, Article 690.11), all PV power generation systems with a DC voltage exceeding 80V attached to or within buildings must be equipped with photovoltaic DC arc fault protection devices, which are required to be capable of reliably detecting and cutting off DC arcs.

690.11 Arc-Fault Circuit Protection (dc). Photovoltaic systems with PV system dc circuits operating at 80 volts dc or greater
between any two conductors shall be protected by a listed PV arc-fault circuit interrupter or other system components listed
to provide equivalent protection. The system shall detect and interrupt arcing faults resulting from a failure in the intended
continuity of a conductor, connection, module, or other system component in the PV system dc circuits.

Exception: PV system dc circuits that utilize metal-clad cables, are installed in metal raceways or enclosed metal cable trays,
or are under ground shall be permitted without arc-fault circuit protection if the installation complies with at least one of the following:
(1) The PV system dc circuits are not installed in or on buildings.
(2) The PV system dc circuits are located in or on detached structures whose sole purpose is to support or contain PV system equipment.

Figure 5 Source: National Electrical Code (NEC 2023. Article 690.11)

29.1.2 An arc-fault circuit-interrupter shall be capable of detecting or interrupting arcing as described in the following :
a) Region A: For all tests, disrupt arcing event in less than 2.5 seconds, and limit energy not to exceed 200 J;
b) Region B: For all tests, disrupt arcing event in less than 2.5 seconds, and limit energy not to exceed 750 J; and
c) Region C: For any test, arcing time equal to or greater than 2.5 seconds, or energy greater than 750 J, the device is considered non-compliant with the stalndard.

Figure 6 Source: UL 1699B Standard

9.2.7 Arc energy and response time measurement
The voltage across the arc gap, the arc duration, and the current through the arc shall be measured and recorded. These measurements are theen used to calculate the total energy generated by the arc prior to detection or interruption. Foor arc duration measurements,
(1) The arc period for AFPEs begins when the arc voltage reaches 10 V and ends when the arc current falls below 250 mA.
(2) The arc period for AFDs begins when the arc voltage reaches 10 V and ends at the indication of an arc event.

Figure 7 Source: IEC 63027:2023 Standard

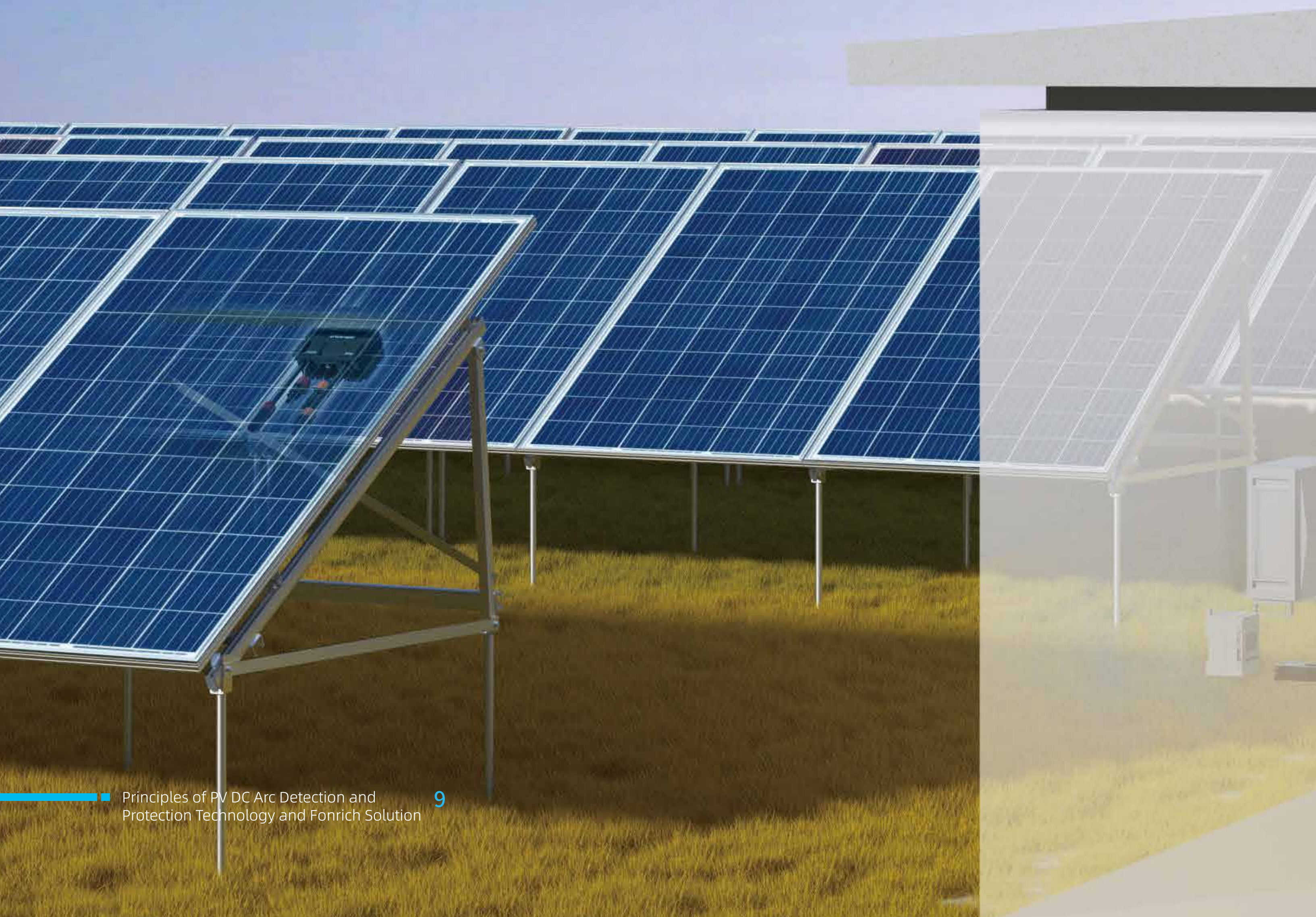
In Europe, the International Electrotechnical Commission (IEC) has relatively delayed its layout in photovoltaic DC arc detection and protection. In the latest version of IEC 63027, a globally unified performance specification has been established for photovoltaic arc fault detection systems, with performance index requirements similar to UL 1699B. Several EU member states have also added mandatory safety testing functions as a prerequisite for subsidies for Commercial & Industrial and residential to install PV systems.

In recent years, China's photovoltaic development speed has been leading the world, and corresponding technical regulations are gradually improving. The National Energy Administration and related institutions have successively issued technical requirements for DC arc fault protection, and gradually promoted the integration with international standards.

At present, the general requirements for DC arc fault protection in different regions are constantly strengthening, which provides a broad market space for the application of photovoltaic DC arc fault protection technology and solutions.

02

Principles of PV DC Arc Detection and Protection Technology and Fonrich Solution



2.1 Principle of PV DC Arc Detection and Protection Technology

The PV DC arc detection and protection device is a professional electrical protection equipment used for detecting and handling arc faults. The core principle is to precisely identify by monitoring and analyzing the current and voltage signals in the circuit and combining them with the characteristic signals generated by the arc. When the arc signal is detected, the device will immediately issue a protection instruction to quickly interrupt the arc period, thereby effectively preventing the further deterioration of the fault.

The characteristics of arc signals are mainly reflected in high-frequency oscillation, current instability and spectral anomalies, etc. Therefore, the detection basis for photovoltaic DC arc fault protection mainly focuses on key indicators such as the variation of current waveforms and the analysis of arc characteristic frequency signals.

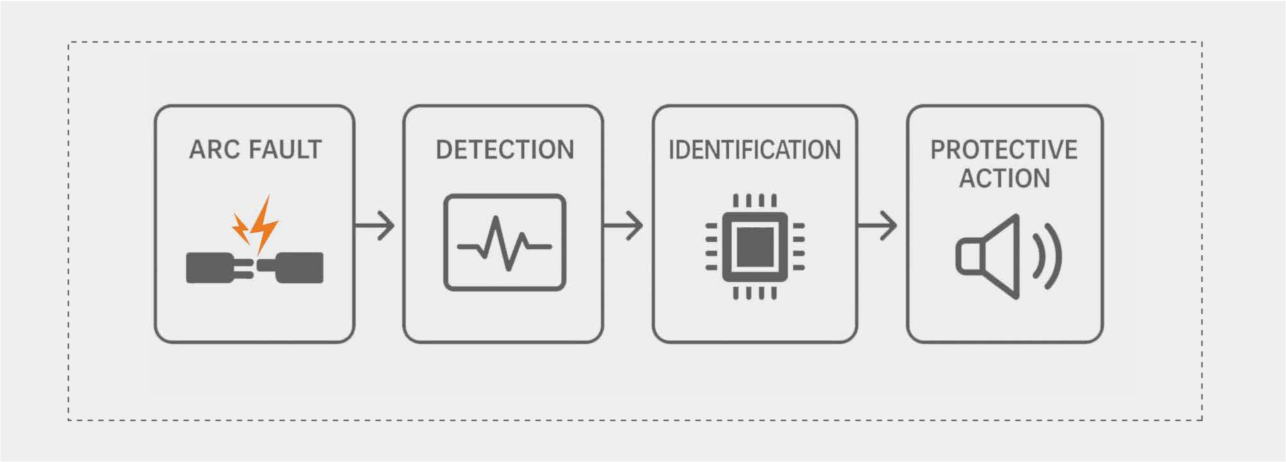


Figure 8: Arc Fault Event

2.2 Traditional Photovoltaic DC Arc Fault Protection Solutions

The traditional photovoltaic DC arc fault protection technology mainly relies on simple waveform and frequency detection, it may achieve certain effects in small-scale applications of DC circuits. However, such traditional solutions face many challenges in practical applications, such as insufficient detection sensitivity, high false alarm rate and difficulty in adapting to complex scenarios. For instance, the high-frequency interference current generated when an inverter starts up is often misjudged as an arc signal. Moreover, in large-scale PV power stations, the interference from long cables makes it even more difficult for traditional photovoltaic DC arc fault protection to achieve precise identification. In addition, traditional photovoltaic DC arc fault protection mainly focuses on photovoltaic inverters with relatively single detection locations, lack of comprehensive solutions.

2.3 Fonrich Solutions and Technical Advantages

In response to the limitations of traditional solutions, Fonrich has launched a comprehensive and professional solution for photovoltaic DC arc fault protection, achieving significant breakthroughs in both technical principles and performance. This scheme adopts high-precision signal analysis technology, which can accurately extract the signature characteristics of the arc from the high-frequency harmonic characteristics, significantly improving the accuracy and reliability of the detection. In addition, Fonrich's solution has extensive system adaptability. Whether it is for residential, commercial and industrial use, or ground-mounted power stations, it can effectively address the complex arc hazard challenges.

The advantages of the Fonrich solution are not only reflected in the improvement of a single indicator, but also in the realization of a comprehensive system solution capability through technological integration. For instance, this solution can be efficiently integrated with other shutdown devices and monitoring platforms to form a comprehensive security protection system. Its overall efficiency far exceeds the simple superposition of the functions of each part.

2.3.1 The inverter/combiner box integrates the AFCI solution

The arc protection solution for inverters/combiner boxes usually integrates the arc detection module with inverters, combiner boxes and other equipment, which helps to improve the integration of equipment and space utilization efficiency, and reducing costs at the same time. However, such schemes mainly provide protection against series arcs and have limited protective effects on parallel arcs. Furthermore, when the detection distance is relatively long, usually exceeding 400 meters, its detection effect will be significantly affected, which limits its application in large-scale and complex PV systems at a large extent.

For PV systems with relatively low safety requirements, small system scale, and simple operating environment, the integrated solution of arc detection module can meet the basic requirements of regulations and provide basic arc protection functions. However, in complex scenarios and high safety requirements, due to its limitations in parallel arc protection and long-distance detection, it cannot fully guarantee the safe and stable operation of the system.

For inverter/combiner box manufacturers that require integrated arc protection function, Fonrich AFD can help them quickly integrate and achieve arc protection function. This type of device can accurately detect the string where the arc is located and efficiently extinguish the arc through the built-in Fonrich AFD.

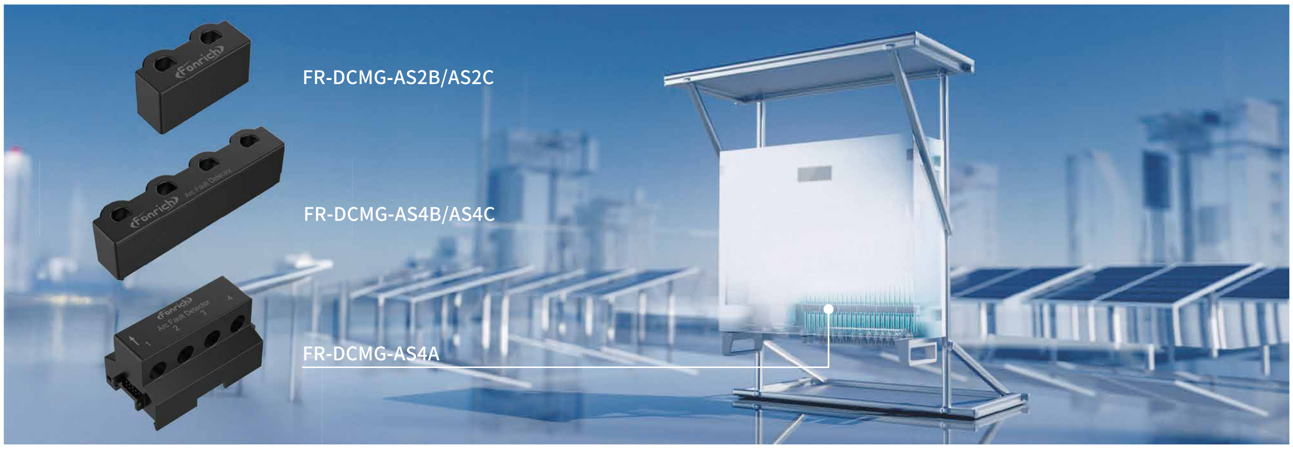


Figure 9: String inverter application

2.3.2 Independent AFCI protection box scheme

The arc protection box scheme, as an external form of integrated arc protection scheme for inverters/combiner boxes, has unique advantages. If it is installed in a PV array, under specific conditions, it can meet the UL1741 regulatory requirements even if RSD equipment is not installed. This is because when the wire harness of the circuit is not converged, parallel arcs will not occur. Cutting off the circuit before the wire harness converges can suppress parallel arcs. This design makes the arc protection box scheme perform well in suppressing parallel arcs. Fonrich arc protection box, as an external installation device, is usually installed at the output port of the PV array or the interface of the inverter. It can directly detect and protect the series arc in the circuit, and is widely compatible with mainstream inverters, with the advantages of easy installation, operation, and maintenance. The photovoltaic DC arc extinction patented technology it adopts not only protects the arc, but also does not affect normal power generation.

However, the arc protection box scheme also has certain limitations. On the one hand, it mainly protects the parallel arc between the arc protection box and the inverter, which cannot fully protect the parallel arc in other positions; On the other hand, the number of protected paths is limited by the type of enclosure, resulting in insufficient flexibility and relatively weak adaptability in different scenarios.

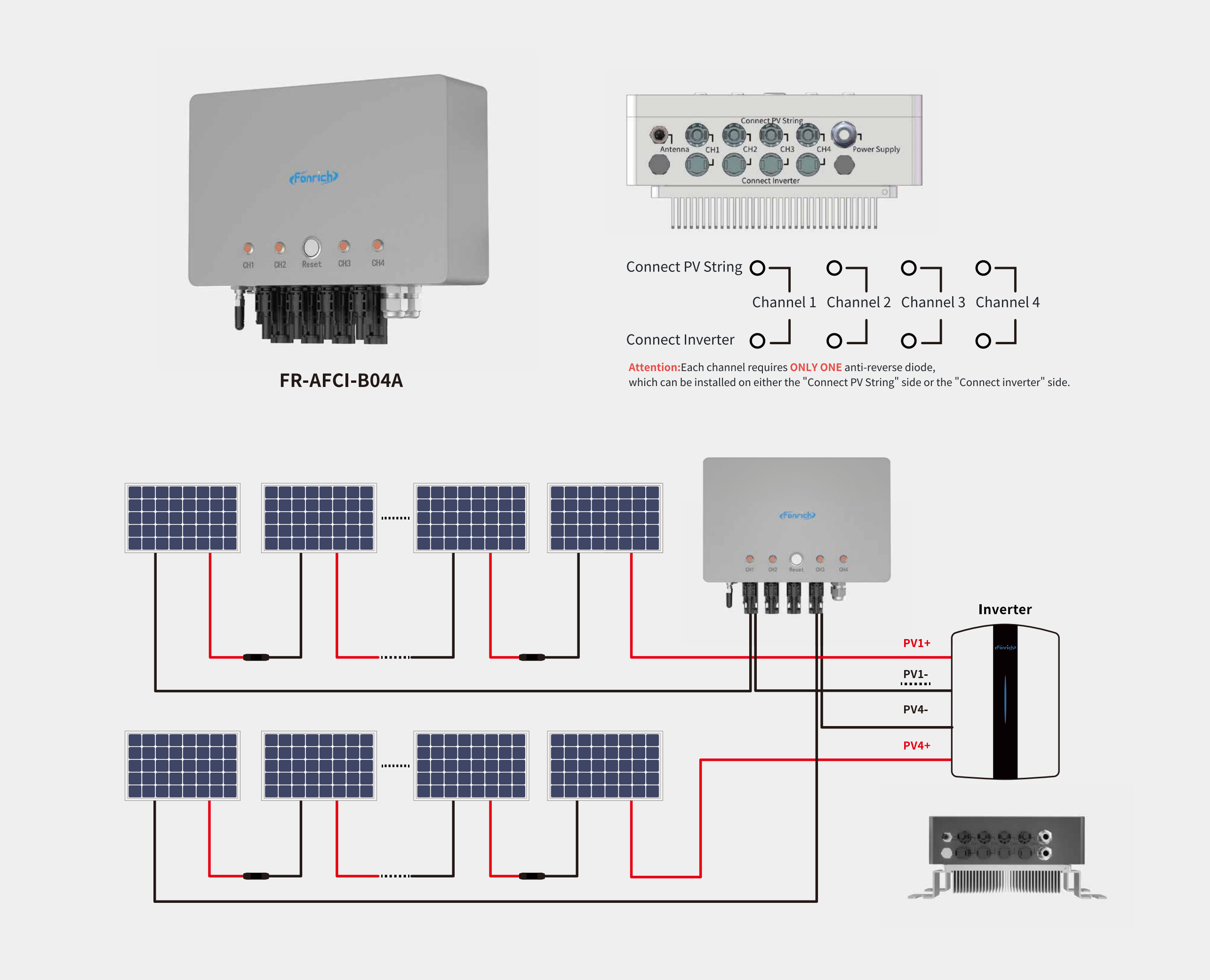


Figure 10: Independent AFCI protection box system connection diagram and wiring terminal labels

2.3.3 Arc Interrupter scheme installed in PV string

Compared with the arc protection box solution, the arc protectors installed in PV strings (hereinafter referred to as Arc Interrupter) has more advantages in many aspects and is more recommended. Arc Interrupter needs to be installed on the first or last module of the photovoltaic string, featuring plug-and-play convenience, which can significantly simplify the installation process and save installation time and labor costs. Meanwhile, it can not only effectively protect series arcs but also precisely safeguard parallel arcs, providing more comprehensive arc protection for PV systems, **ensuring the safe and stable operation of the system. After installation, it can also meet the relevant regulatory requirements of UL1741.** In addition, the Arc Interrupter can be optionally equipped with a control unit, which can monitor its working status in real time through PLC communication, in order to timely grasp the operation state of the equipment, predict potential faults in advance, enhance the timeliness and effectiveness of system maintenance, and further improve the reliability and safety of the PV system.

Figure 11: Arc Interrupter

In practical applications, the flexibility and adaptability of the Arc Interrupter scheme are also more outstanding. It is not limited by the type of enclosure and can be flexibly configured according to the different field requirements. Whether it is a small distributed PV system or a large centralized PV power station, it can be easily adapted to provide reliable arc protection. In terms of cost, Arc Interrupter also demonstrate a high cost-performance ratio. Their reasonable price setting enables a wide range of users to effectively control cost input while ensuring the safety of PV systems, achieving a win-win situation of economic and safety benefits.

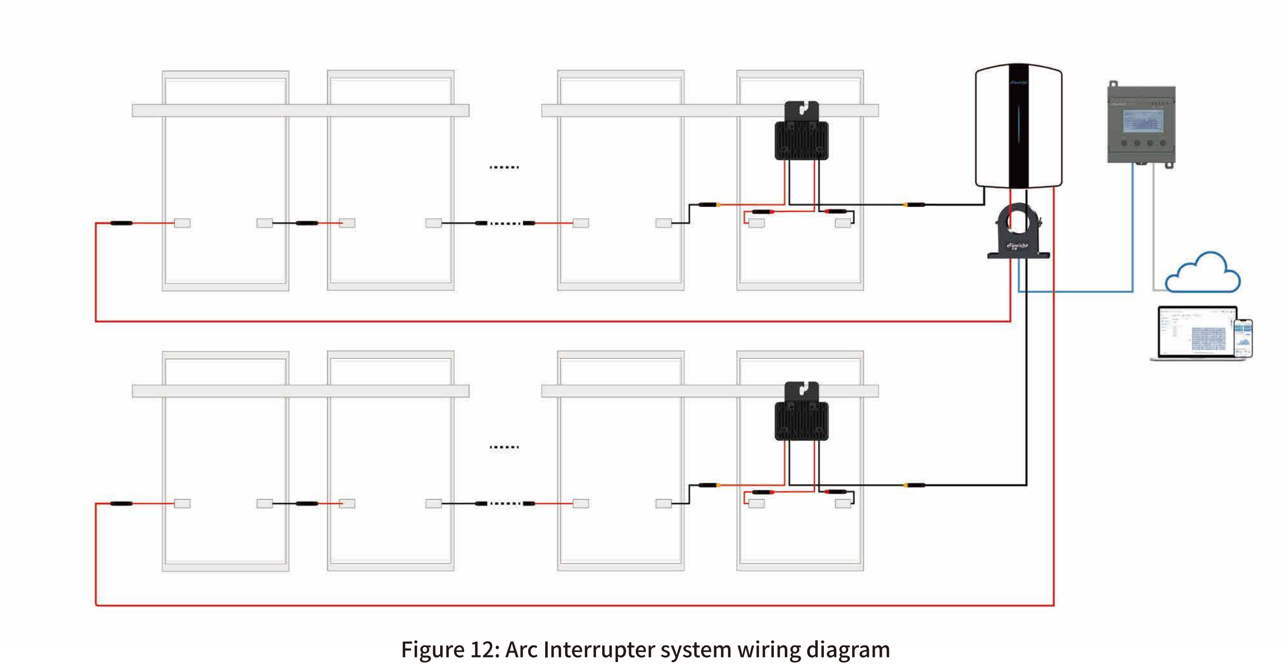


Figure 12: Arc Interrupter system wiring diagram

2.3.4 Module-level RSD/optimizer integration of AFCI solution

As regulations regarding module-level RSDs gain traction and are implemented worldwide (referred to as RSD hereinafter, all RSD rapid shutdown devices mentioned in this article are at the module level), the improvement of power station safety standards in various countries has become an inevitable trend. In this situation, Fonrich, leveraging its technological advantages, has deeply integrated RSD and AFCI technologies and launched a RSD solution with arc protection functionality. This solution not only effectively suppresses the fire risk caused by electric arcs, but also provides a solid protective barrier for the safe operation of the power station.

In fire accidents caused by electric arcs, the occurrence frequency of series electric arcs is relatively higher. However, once parallel electric arcs are formed, their degree of danger becomes more serious.

The RSD integrated arc protection solution offers significant advantages in practical applications. Each RSD independently detects arc faults, establishing multiple layers of protection and enhancing the stability and reliability of detection. Positioned close to common arc fault locations within the PV array, the detection devices enable faster response and shorter fault handling times. Additionally, this detection method is not affected by the inverter installation location, ensuring comprehensive and effective arc

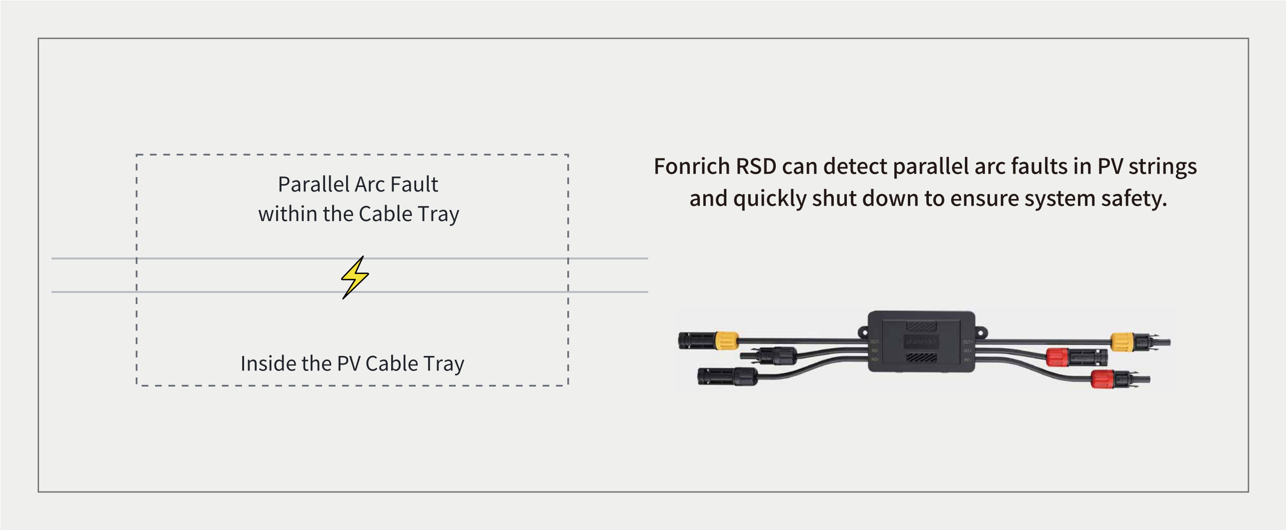


Figure 13: Parallel Arc Fire Illustration

For scenarios with RSD requirements, the cost increase involved in adding arc protection functions is extremely small, but the safety benefits it brings are significant and can achieve a qualitative leap in the safety guarantee level of power stations. Perhaps some readers may raise a question: Can the RSD action be directly detected and controlled through the inverter to replace the current RSD integrated arc protection solution? However, it should be made clear that there are essential differences in practical effects between these two schemes. In the linkage scheme, the alarm device and the protection action device need to rely on additional communication means, and this communication is usually PLC wireless communication, whose stability is hard to be effectively guaranteed. This leads to the fact that the interlocking scheme can ultimately only achieve the effect of integrated arc protection in the inverter, which is essentially different from the module-level arc protection scheme. A more in-depth analysis of this difference will be elaborated in detail in Chapter Four.

2.3.5 Comparison of protection Effects of various schemes

When comparing different arc protection schemes, it can be clearly seen that there are differences in the protection effects of each scheme. The protection of DC series arcs is relatively simple. It only requires cutting off at any position in the circuit to achieve arc extinguishing. Therefore, most arc protection schemes can effectively protect series arcs. However, the protection of parallel arcs is much more complex, and the requirements for arc extinguishing are also more stringent. In the simple case of no other series in parallel connection, in order to effectively extinguish the arc, the circuit must be interrupt on the side close to the photovoltaic module. In complex cases where parallel strings exist, the arc extinguishing of the parallel arc requires the simultaneous cutting off of the circuits at both ends of the arc, that is, not only the side close to the photovoltaic module, but also the side close to the inverter. Only in this way, the parallel arc can be completely extinguished.

This difference makes the protection of parallel arcs becomes a key indicator for evaluating arc protection schemes. Different arc protection schemes have varying capabilities in parallel arc protection, ranging from partial protection to full protection. Therefore, when choosing an arc protection scheme, its protective effect on parallel arcs must be fully considered to ensure the final safety performance. By comparing the protection effects of different schemes, the most suitable arc protection scheme for a specific PV system may be selected more scientifically and reasonably, thereby maximizing the safety and reliability of the system.

Arc type / Protection scheme	Series arc	Parallel arc		
		Inside the PV array	Inside the string cable tray	At the inverter/combiner box
Type-1: AFCI integrated in the inverter/combiner box	√	×	×	×
Type-2: Independent AFCI protection box	√	×	Depend on installation location①	√
Type-3: Arc Interrupters are installed in photovoltaic strings	√	√	√	√
Type-4: Type-1 is connected with module-level RSD/optimizers	√	×②	×②	×②
Type-5: Module-level RSD/optimizer integrated with AFCI	√	√	√	√

Note ①: Installing it on the side of the PV array can protect this item, but installing it at the inverter/busbar cannot.

Note ②: The inverter cannot detect the parallel arcs, and when arcs occur, it cannot ensure the complete issuance of the shutdown command.

Note : "√" is defined as "Can Protect", "×" is defined as "Cannot Protect".

03

Applicability and Economy of Different Shutdown and Photovoltaic DC Arc Fault Protection Schemes

After discussing the technical principles and performance of different arc protection schemes, we further focused on the applicability and economy of these schemes in practical applications. Choosing an appropriate arc protection scheme is not only about technical considerations, but also involves the balance between economic costs and scene requirements. The following contents will conduct an in-depth analysis of the recommended protection schemes in different scenarios, and explore their applicability and economy to help project decision-makers maximize cost-effectiveness while meeting security requirements.

When choosing a photovoltaic DC arc fault protection scheme, it is necessary to comprehensively consider the scene requirements, protection effect and economic cost. The following are the recommended protection schemes in different scenarios:

For scenarios where only regulatory requirements need to be met, integrating arc protection functions in inverters or combiner boxes is an economical and practical option, which can reduce costs while meeting basic regulatory requirements. In the renovation projects of old power stations, the external arc protection device has become an ideal choice due to its convenient installation and small modification to the existing system. For those projects that are willing to pursue higher safety performance within a certain cost range, string arc protectors are an excellent choice that balances economy and safety. Finally, for projects with high safety requirements and a pursuit of more functions, the RSD or optimizer integrated arc solution can provide more comprehensive protection and functional expansion.

The following content will list several common arc requirements and analyze the applicable arc protection schemes one by one.

Scenario requirements	Recommend schemes
It is sufficient to meet the regulatory requirements	Type-1: AFCI integrated in the inverter/combiner box
Renovate the old power station and add arc protection function	Type-2: Independent AFCI protection box or Type-3: Arc interrupter installed in the photovoltaic string
All types of arc protection	Type-3: Arc interrupter are installed in photovoltaic strings
There is already a requirement for RSD installation	Type-5: Module-level RSD/optimizer integrated with AFCI

Figure 13: Arc Fault Solution Recommendations by Requirement

3.1 Principle of PV DC Arc Detection and Protection Technology

For PV power stations that have been built but do not have arc fault protection functions, as time goes by and the equipment ages, the risk of arc faults increases day by day. Carrying out arc fault protection transformation for this type of power station is an urgent problem to be solved. However, the construction of adding module-level protection equipment is highly complex and involves a large amount of work, while replacing existing equipment, such as inverters, also faces the predicament of high hardware costs and great construction difficulty. This leaves many property owners in a dilemma when making renovations. For this application scenario, Fonrich recommends the use of an independent external photovoltaic DC arc fault protection device, which should be installed in series in the DC circuit. This scheme has the advantages of low construction difficulty, controllable cost and short renovation period. It can quickly and efficiently add photovoltaic DC arc fault protection function to the power station, significantly improving the safety performance of the power station.

3.2 Conventional New PV power station scenarios

For newly installed power stations, to meet regulatory requirements with minimal additional cost, inverters or combiner boxes with integrated AFD functions can be directly selected.

- In residential or C&I scenarios, selecting inverters with integrated photovoltaic DC arc fault protection meets regulatory requirements without altering traditional system design or adding significant costs. The inverter’ s arc protection can either be self-developed or equipped with Fonrich arc detection modules, with Fonrich modules enabling faster development, quicker market entry, and stronger competitiveness.
- In Utility-Scale PV stations, choosing combiner boxes with integrated DC arc fault protection provides wide detection coverage, controlled costs, and no need to modify existing designs.Loose connections in new installations often cause fires; using such solutions can protect station assets. Equipping combiner boxes with Fonrich AFD modules avoids increased R&D complexity and accelerates time-to-market.
- To achieve affordable series and parallel arc protection onsite, a string arc protector can be selected. The cost is comparable to adding one RSD per string, but significantly enhances arc protection, especially for severe parallel arcs.

3.3 PV power station scenarios with high safety requirements

For power stations with extremely high requirements for arc fault protection or seeking advanced functions such as module-level data detection, an integrated arc RSD (or optimizer) is suitable.

After RSD integrates the photovoltaic DC arc fault protection function, it can achieve module-level shutdown, providing more thorough protection and better suppression of excess fires. It is recommended for use in scenarios with very high safety requirements such as grain silos and gas stations. In addition, high-configuration RSD can achieve module-level data monitoring. This solution is recommended for power stations seeking multiple functions such as scientific research projects and refined operation and maintenance. Fonrich RSD can detect key data such as power, voltage, current, temperature, power generation, and arc faults, bringing more added value to users through digital power stations.

After RSD integrates the photovoltaic DC arc fault protection function, it can achieve efficient shutdown at the module level, providing more thorough protection and better fire suppression effect. This solution is recommended for use in scenarios with extremely strict safety requirements such as grain silos and gas stations. In addition, high-configuration RSD can also achieve module-level data monitoring, which is suitable for power stations with multi-functional requirements such as scientific research projects, refined operation and maintenance, bringing more added value.

It is particularly important to note that the scheme where the inverter is equipped with AFCI arc detection and then connected with RSD to achieve turn-off has essential differences from the RSD integrated AFCI scheme:

- **RSD integrated scheme: Detection within the PV array is more timely, and protection actions are taken immediately after detection, ensuring that the RSD is turned off within 2.5 seconds after the arc occurs.**
- **Inverter linkage scheme: The detection effect of long circuits will be compromised. After detection, the shutdown command is issued relying on wireless communication, which can only ensure that the inverter performs protection actions within 2.5 seconds after the arc occurs.**

RSD integrated arc protection solution	Inverter detection arc linkage RSD shutdown scheme
Detection is timely within the PV array	The detection effect of long circuits will be compromised
Immediate action protection after detection	After detection, a shutdown command is issued relying on wireless communication
It can be ensured that the RSD is turned off within 2.5 seconds after the arc occurs	It can only be guaranteed that the inverter operates within 2.5 seconds after the arc
Parallel arc detection is precise	Parallel arc detection cannot be guaranteed

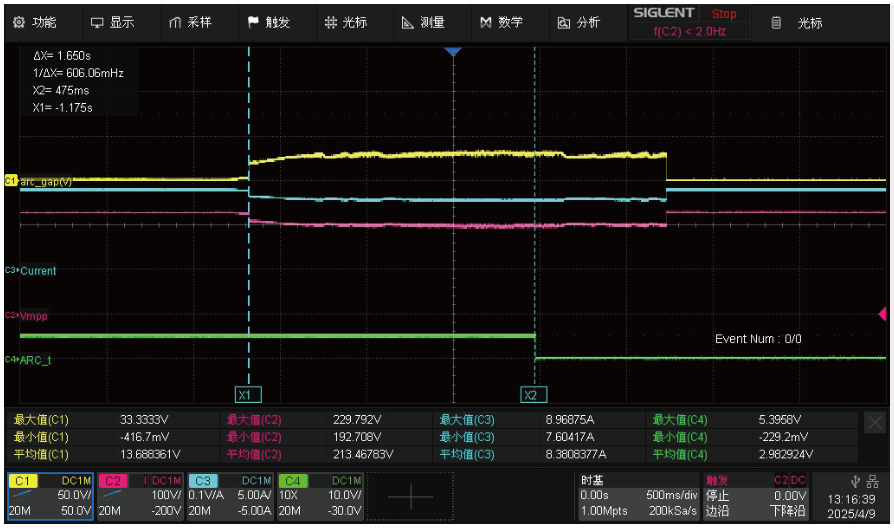
04

Principles of Photovoltaic DC Arc Detection and Protection Technology and Fonrich Solution

Photovoltaic DC arc fault protection equipment typically includes an arc fault detection device (AFD) for arc fault detection and an arc fault protection device (AFPE, AFI, Fonrich RSD Integrated Arc Protection Function version (hereinafter referred to as Fonrich RSD) that can both detect and interrupt arcs. Fonrich has tailored appropriate DC arc fault protection solutions for different types of PV power generation systems. To verify the functionality and effectiveness of Fonrich Photovoltaic's DC arc fault protection solution, TÜV Rheinland was fully involved in the formulation of the empirical test plan and on-site witnessing to verify the product performance in real scenarios. Such tests are closer to the actual scenarios than those in the laboratory and are more representative.

4.1 Scheme A: Arc Detection Module AFD Scheme and Verification, TÜV Rheinland witnessed the entire process

Photovoltaic arc fault protection equipment	Fonrich Arc Detection Module AFD
Verification purpose	When arc faults occur at various points within the PV array, the AFD module can detect them normally and issue alarm signals.
Verification method	Build a real typical photovoltaic string architecture and artificially create arc faults within the PV array. The fault points include the positive and negative poles of the string and the middle position of the string.
Verification process	Step 1: Create an arc fault near the inverter at the positive terminal of the string to simulate the arc caused by reasons such as module aging and insulation damage in actual operation. Step 2: Detect the alarm signal of the AFD module when an arc occurs, and synchronously record the voltage and current information of the arc. Check if the AFD module can detect arc signals in a timely manner and issue alarm signals correctly. Step 3: Change the arc fault location to the negative pole of the string and the middle position of the string, and repeat steps 1 and 2.
Verification Results and Analysis	AFD detection module: It can promptly detect arc faults within the PV array and quickly issue alarm signals to notify relevant equipment to perform protective actions, effectively extinguishing arcs and protecting photovoltaic modules and circuits from further damage.

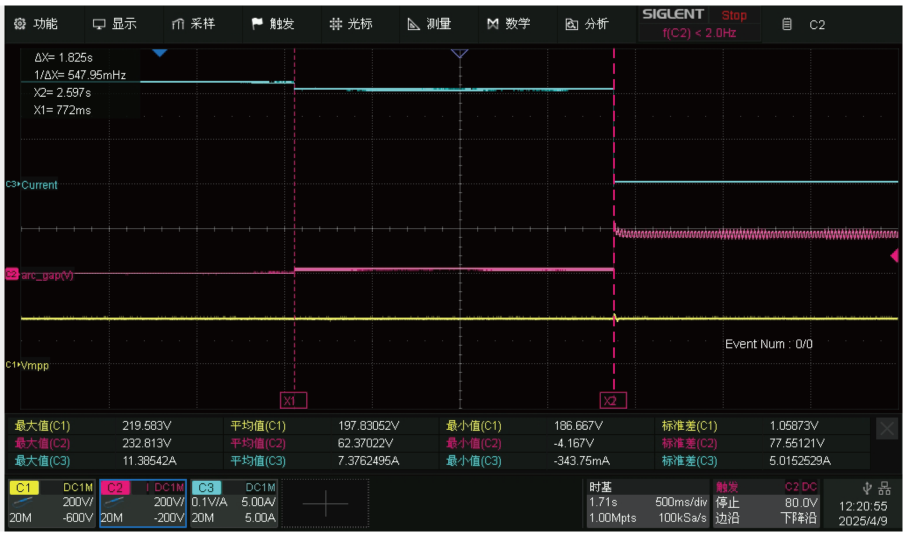


AS4A Arc Fault — Signal Definitions

▲X: Arc Protection Response Time
X1: Arc Initiation Time
X2: Arc Time
C4: Alarm Signal
C3: String Current
C2: System Voltage
C1: Arc Voltage

4.2 Scheme B: External String PV DC Arc Fault Protection Scheme and Verification, TÜV Rheinland witnessed the entire process

Photovoltaic arc fault protection equipment	Two types of external string arc fault protection schemes were tested respectively: arc protection boxes and string arc interrupter
Verification purpose	When arc faults occur at various points within the PV array, both the Fonrich arc protection box and the string arc interrupter can normally detect the arc and cut off the circuit to extinguish it.
Verification method	Build a typical photovoltaic string architecture and artificially create series arc faults within the photovoltaic array to ensure that the fault point is within the internal circuits of the array.
Verification process	Step 1: Create an arc fault near the inverter at the positive terminal of the string to simulate the arc caused by reasons such as module aging and insulation damage in actual operation. Step 2: Observe and record the protection actions of the arc protection box/string arc interrupter, and record the voltage and current data of the arc to determine whether the arc has been extinguished and whether the protection is effective. Step 3: Change the arc fault location to the negative pole of the string and the middle position of the string, and repeat steps 1 and 2.

Verification Results and Analysis	After detecting the arc on the DC side of the photovoltaic system, the arc protection box/string arc interrupter can promptly act to protect the string where the arc occurs, cut off the faulty circuit, effectively prevent the further spread of the arc, and safeguard the safety of the entire photovoltaic system.
Fonrich AFPE Arc Fault Protection ▲X：Arc Protection Response Time X1：Arc Initiation Time X2：Arc Time C3：String Current C2：Arc Voltage C1：System Voltage	

4.3 Scheme C: Module-level Photovoltaic DC Arc Fault Protection Scheme and Verification: TÜV Rheinland witnessed the entire process

Photovoltaic arc fault protection equipment	Fonrich RSD
Verification purpose	When arc faults occur at various points within the PV array, Fonrich RSD can normally detect the arc and cut off the circuit to extinguish it.
Verification method	A typical photovoltaic string architecture is built, with an RSD device installed on each module within the array. A series arc fault is artificially created within the photovoltaic array to ensure that the fault point is within the internal circuit of the array.

Verification process	Step 1: Create an arc fault near the inverter at the positive terminal of the string to simulate the arc caused by reasons such as module aging and insulation damage in actual operation. Step 2: Observe and record the protection actions of the photovoltaic DC arc fault protection equipment at the module-level. Record the voltage and current data of the arc to determine whether the arc has been extinguished and whether the protection is effective. Step 3: hange the arc fault location to the negative pole of the string and the middle position of the string, and repeat steps 1 and 2.
Verification Results and Analysis	When an arc fault occurs, Fonrich RSD can respond quickly, immediately cut off the current in the faulty circuit, and successfully extinguish the arc.

Fonrich RSD Arc Fault Protection

▲X: Arc Protection Response Time

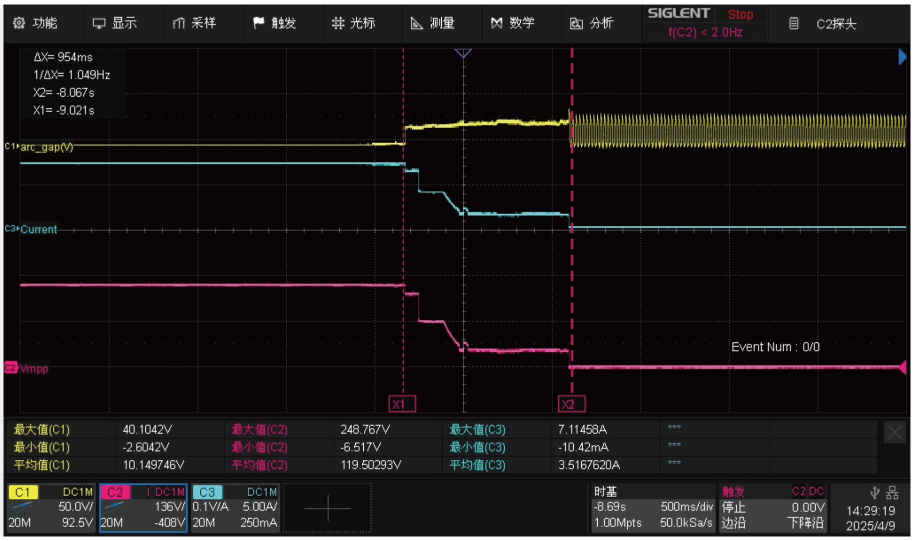
X1: Arc Initiation Time

X2: Arc Time

C3: String Current

C2: System Voltage

C1: Arc Voltage



05 / Chapter Five Summary and Outlook

With the advancement of the global "dual carbon" goal, PV power generation has become a main force in energy transformation. However, as the installed capacity of photovoltaics continues to grow, safety issues caused by DC arcs have gradually become a focal point of industry attention. DC arcs are characterized by strong concealment, high harmfulness, and difficulty in detection, posing severe challenges to the long-term safety of PV systems.

Through analysis of current technologies and verification of practical cases, it can be seen that photovoltaic DC arc fault protection (arc fault circuit interrupter) technology has become a core means to address photovoltaic DC arc issues. In response to complex risks in different application scenarios, the industry has gradually emerged with a series of efficient solutions. Future photovoltaic DC arc fault protection systems not only need to achieve accurate detection in key scenarios, but also need to balance stability and economy for wider promotion and application.On the other hand, the continuous improvement of regulations and standardization requirements in various countries has also provided strong support for the development of photovoltaic arc fault protection technology. The safety standards for

PV systems are moving towards greater systematization and internationalization, which requires enterprises to continuously innovate in technological research and development as well as application practices, proactively promote standard alignment and participate in international cooperation. Meanwhile, the in-depth involvement of third-party certification institutions will further promote the large-scale implementation and optimization of DC arc detection and protection solutions.

Looking ahead to the future, the high-quality development of the PV industry not only relies on the expansion of installed capacity, but also requires comprehensive assurance of system safety, reliability, and sustainability. Through the joint drive of technology and standards, DC arc detection and protection technology will play a more important role in the mission of "safeguarding photovoltaic safety" and provide solid support for the global energy green transformation. TÜV Rheinland will continue to work together with industry partners to safeguard photovoltaic safety innovation, jointly help achieve the "dual carbon" goal as soon as possible, and open a new

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