



Arc Fault Circuit Interrupter (AFCI) for PV Systems Technical White Paper

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Preface

Huawei Technologies Co., Ltd. (Huawei for short) has launched inverters with the intelligent DC arc detection (AFCI) function for distributed (including residential) PV systems. As of May 2020, such inverters have been employed in 54 countries, with a total of 25,000 units shipped globally.

To verify the performance and availability of arc-fault circuit interrupter (AFCI), Huawei entrusted the China General Certification Center (CGC) to complete comprehensive evaluation, with its results showing that **Huawei inverters with the AFCI function meet the requirements of UL 1699B-2018 "Safety Standard for PV DC Arc Fault Circuit Protection." The detection scope, detection precision, and shutdown response time reach the L4 level specified in the CGC/GF 175: 2020 "Technical Specifications for Arc Detection and Rapid Shutdown Performance Evaluation."**

CGC and Huawei jointly released the *Technical White Paper on Intelligent DC Arc Detection (AFCI) for PV Systems* to enable the industry to better understand AFCI technology. The white paper describes in detail the development background, technical principles, technical difficulties and features, verification and evaluation results, and application prospects of AFCI technology, with the following aims:

- (1) Provide reference for PV power plant development enterprises and other parties to accurately understand and use products with the AFCI function.
- (2) Provide a basis for technological development and promotion, as well as for enterprises to continuously improve their products based on changing situations and application requirements.



01

Technology Development Background

According to the International Renewable Energy Agency (IRENA), global grid-connected PV capacity reached 580.1 GW at the end of 2019, to which China contributed 204.3 GW.

Distributed PV, among various power generation forms, is highly suited for distributed power supply construction due to its unique advantages; therefore, China has attached great importance to its development. In recent years, China has promoted many incentive policies at the national and local levels, boosting the development

of distributed PV in the country. Figure 1-1 shows the proportion of distributed PV among the total PV installations from 2016 to 2019 in China. It can be observed that the proportion had been growing in the past 4 years. In addition, in China, residential PV has been a highlight in distributed PV system in recent years. According to the China Photovoltaic Industry Association, the total installed capacity of residential PV in China reached 10.1 GW at the end of 2019, covering over 1.08 million homes, more than 50 times that in 2015.

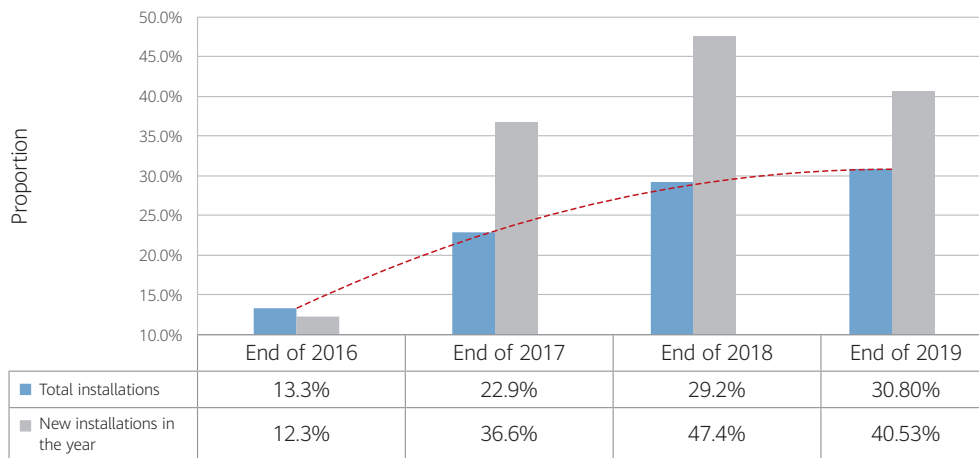


Figure 1-1 Proportion of distributed PV systems among the total PV installations in China

Figure 1-2 shows distributed PV applications and system types. Distributed PV features small single-plant capacity, scattered site locations, complex application scenarios and system types, poor controllability, and difficult O&M. In addition, distributed PV poses high requirements in

terms of safety as it is deployed on the power consumer side, mostly in industrial or residential areas. These features of distributed PV render intelligent methods the foundation for enhancing the safety of PV plants, while also preventing property loss and personal injury,

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thereby achieving sustainable development. In addition, in distributed PV, the mainstream deployment method involves deploying PV modules on various buildings, including building applied photovoltaics (BAPV) and building integrated photovoltaics (BIPV). As such, electrical safety is the focus of accident prevention for this type of power generation form. Figure 1-3 shows the electrical structure of a typical small-sized distributed PV system. As shown in the figure, the focus of the AC lies in the

quality and safety of power supply from the electrical safety perspective, and that of the DC lies in electrical fire, electric shock, and lightning strike accidents. The safety standards and safety protection technology concerned with the AC are currently mature; however, there is still room for improvement in terms of the DC. As such, the IEC and countries across the world are focusing on the formulation of standards concerning the DC.

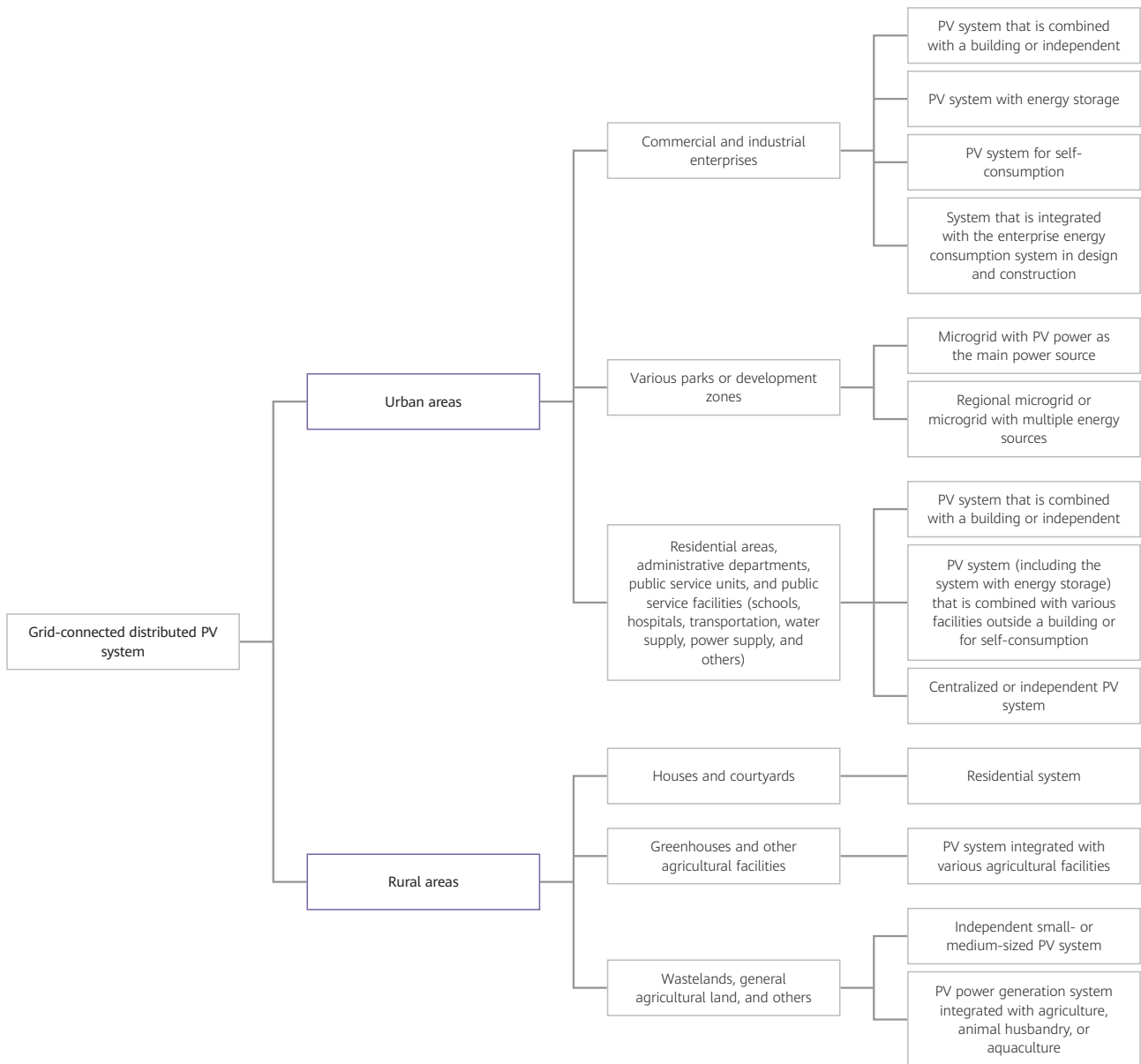


Figure 1-2 Application scenarios and system types of distributed PV

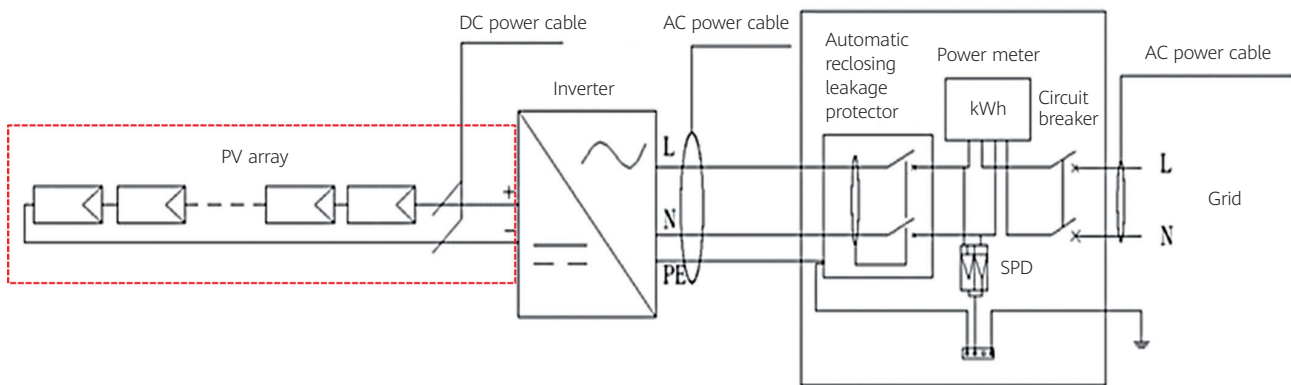


Figure 1-3 Electrical structure of a small-sized distributed PV system

Currently, the electrical safety design of PV arrays mainly complies with IEC 62548 "Photovoltaic (PV) arrays - Design requirements." This standard stipulates the design requirements in terms of electric shock protection, overcurrent protection, array grounding insulation resistance and residual current monitoring and response, lightning and overvoltage protection, as well as selection and installation of electrical devices. The analysis of various accidents has proven that current standards are not comprehensive and effective enough. For example, the factors affecting the design of the current-carrying capacity of DC cables in the preceding standard are too general; the overcurrent protection device selected according to the

standard does not sufficiently address accident prevention; and due to the limitation of technical conditions, only a reference appendix is provided for arc detection and fault response, without specific design requirements proposed.

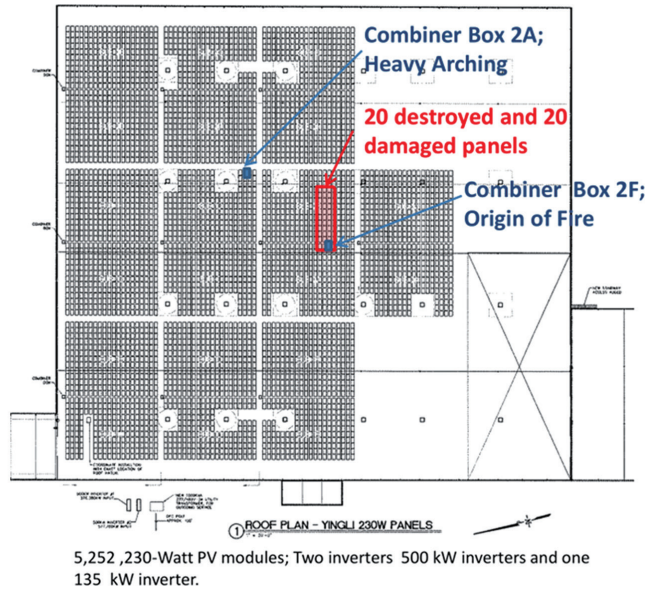
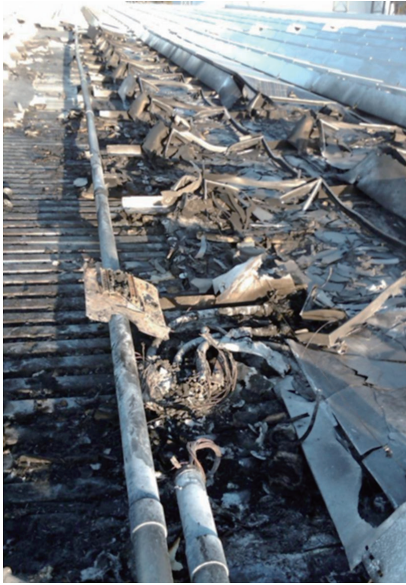
In PV safety accidents that occur globally, electrical fires occur most frequently and result in the greatest losses. For example, in Netherlands, in the residential PV field, 23 accidents involving fires occurred in 2018, accounting for 0.14‰ of the total number of PV installations. Distributed PV systems in China have also experienced more than 10 major fire accidents, similar to those shown in the following pictures.



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The majority of PV plant fire accidents are caused by DC arcing. The following figure shows a fire accident in a PV plant in the United States, with the subsequent

investigation finding that the component overheated due to two arcs, causing the combiner box to set on fire.



As shown in Figure 1-4, there are three types of DC arcs: series arcs, parallel arcs, and arcs to ground. The probability and frequency of series arcs is the highest (about 80%) due to the electrical structure and PV power generation

characteristics. Parallel arcs and ground arcs are less likely to occur, but they are more dangerous. Figure 1-5 shows how a fire occurred in a distributed PV plant in China based on the subsequent investigation.

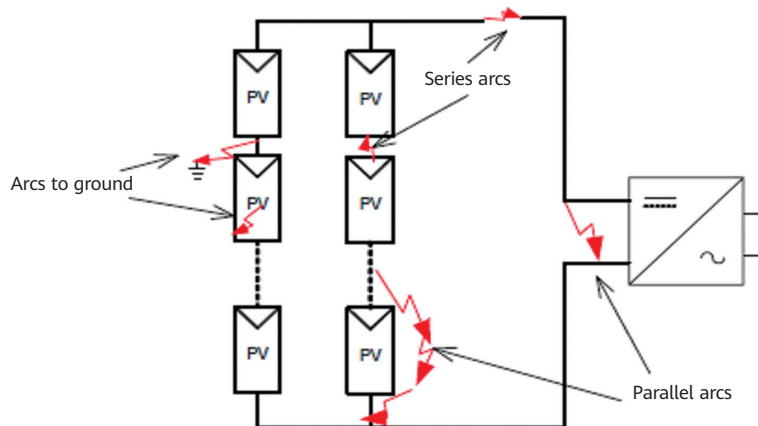


Figure 1-4 Arc types in a PV array

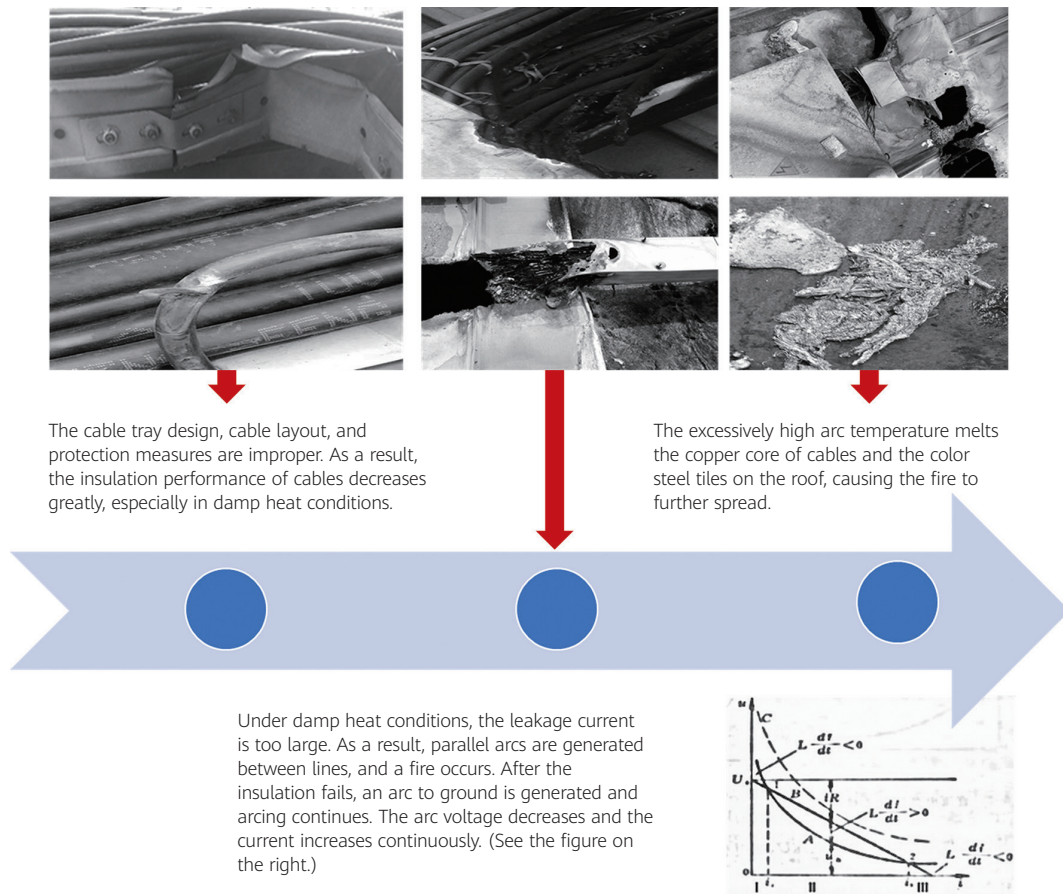


Figure 1-5 Fire cause illustration

To summarize, distributed PV is one of the main forms of PV power generation, and has promising application prospects. However, electrical fires — mainly caused by DC arcing — are the primary risk that needs to be prevented for distributed PV systems. Therefore, it is

essential that comprehensive measures are employed, especially intelligent arc detection and rapid shutdown technologies, in order to improve the safety and control level of PV plants.



02

Technical Description

2.1 AFCI Technical Principles

An arc is a glow phenomenon caused by the ionization of air when an electric conductor is close to another conductor (or ground), and the voltage between them breaks down the air.

An arc produces high temperatures and sometimes can result in open flames. In an electrical system, arcs not only cause the surrounding insulation materials to break down or carbonize and become ineffective, but they can also easily ignite nearby materials.

In a PV system, arcs may be caused by loose terminals, poor contact, broken cables, aging, carbonized, or damaged insulation materials, or damp and corrosive wires. Electric arcs are likely to occur as there are many wiring terminals on the DC side of the PV system.

Figure 1-4 shows the types of arcs that may be generated in a PV array. In principle, an arc can be approximately equivalent to a series connection between a variable resistor and voltage source (as shown in Figure 2-1), and the arc voltage increases in turn with the current and clearance.

The arc model is a time-varying nonlinear model. An arc signal is similar to a white noise signal, and the energy of the arc signal is distributed on almost all spectrums, represented by an increase in energy of different frequency bands, as shown in Figure 2-2. In this figure, there is an obvious spectrum difference between an arcing and non-

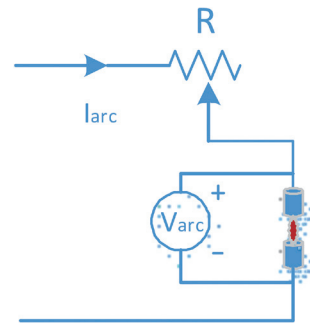


Figure 2-1 Arc approximate equivalent circuit

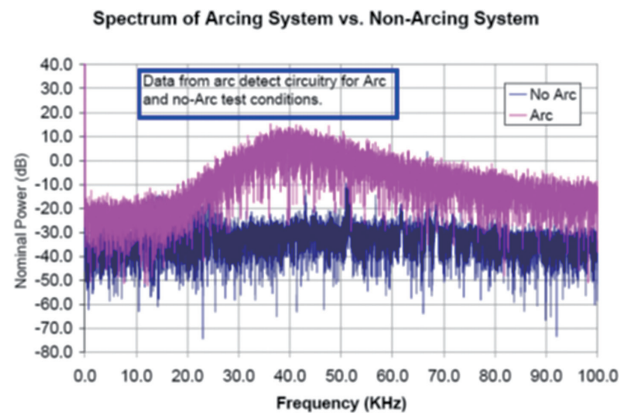


Figure 2-2 Spectrums of arcing vs. non-arcing systems

arc system, meaning that **arc generation in a circuit can be determined by monitoring electrical parameters and spectrum changes in the system.**

The energy of the arc characteristic signal decreases as

the input cable length and arc current increases, as shown in Figure 2-3. In arc detection, both false alarm raising and missed alarm raising need to be prevented as they

exacerbate an accident. In most cases, the **accumulated arc energy before protection is used as a key parameter**, which is used to set indicators for measuring AFCI precision.

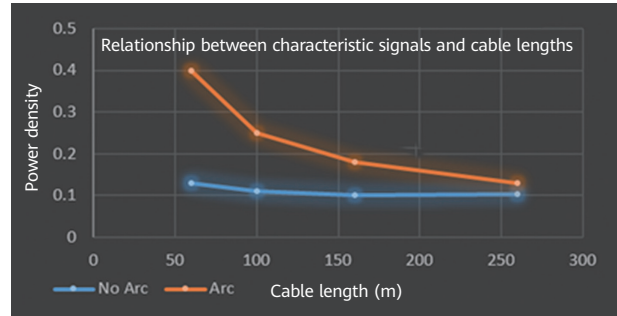
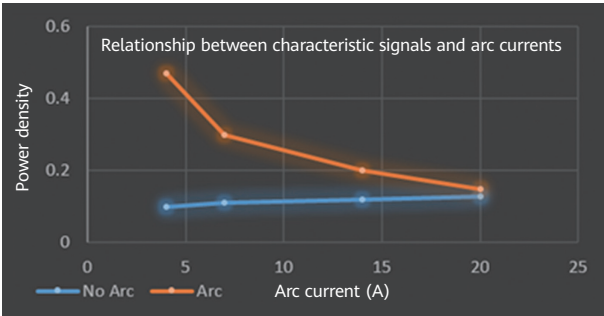


Figure 2-3 Relationship between arc characteristic signal energy and arc current/cable length

Figure 2-4 and Figure 2-5 show the simulated equivalent network requirements for AFCI function detection.

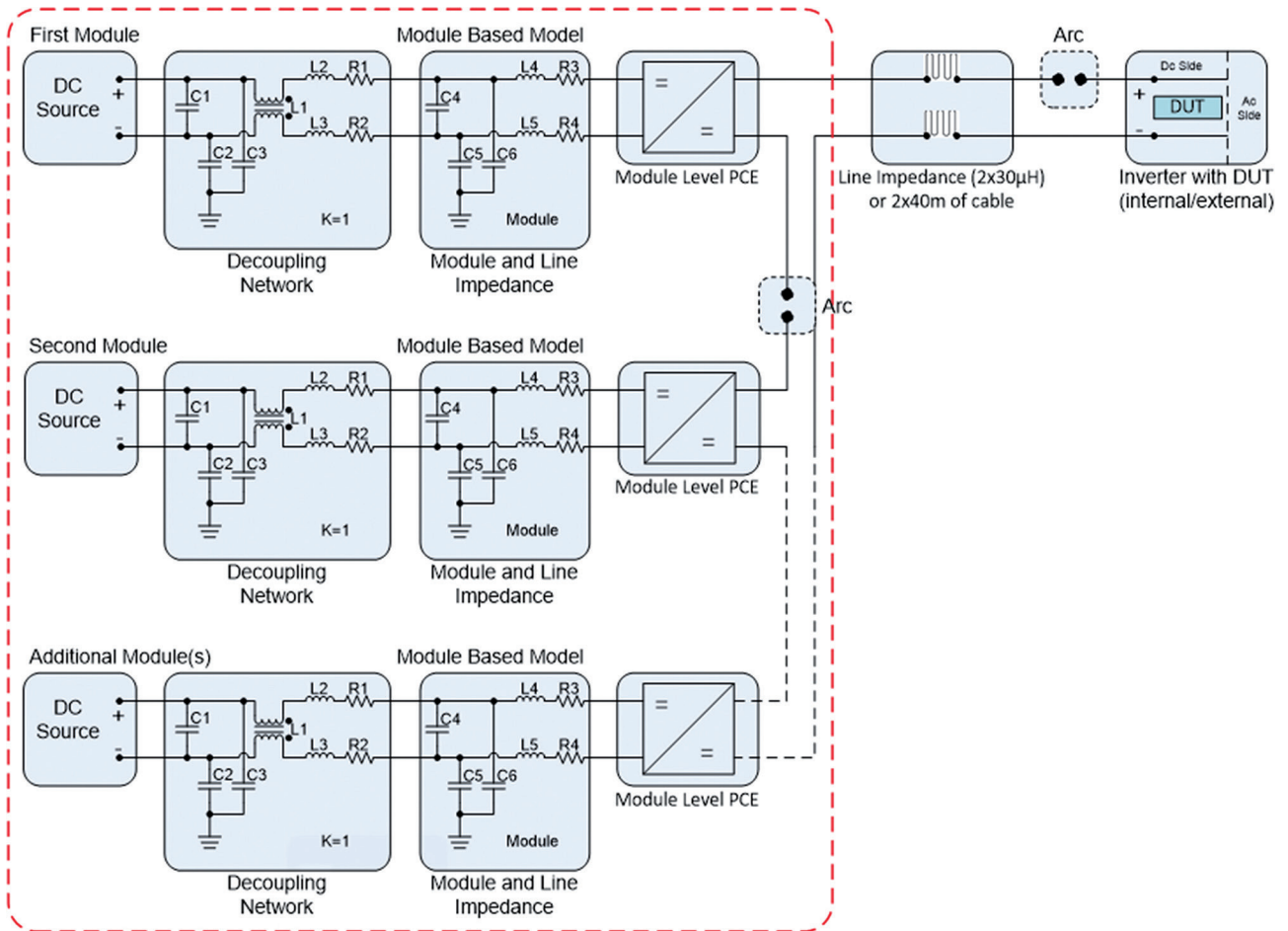


Figure 2-4 AFCI simulated impedance network (with optimizers)

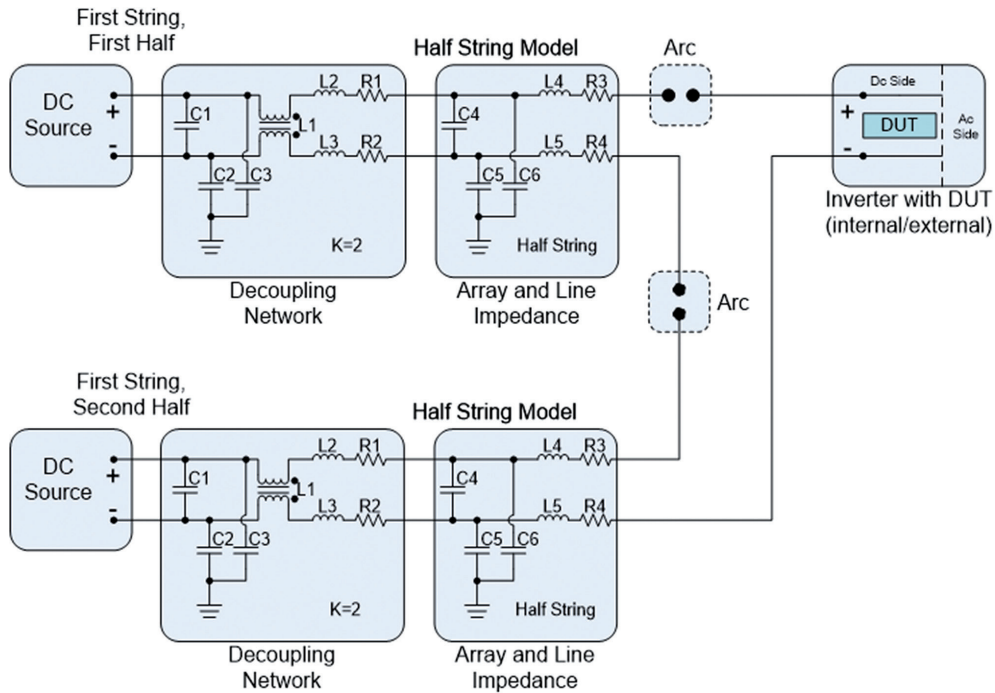


Figure 2-5 AFI simulated impedance network (without optimizers)

2.2 Difficulties in AFI Technology Development

Currently, DC arc detection mainly uses the arc current/voltage frequency domain, including (but not limited to) characteristic information such as the frequency point, energy, and variation, to perform analysis and determination. In fact, some vendors use the supplier-provided integrated algorithm package before performing commissioning using different threshold parameters. Given the arc detection principle, existing detection solution, and technical level, the following difficulties need to be addressed:

(1) Noise adaptability

The onsite running environment of devices is complex. The arc detection algorithm and threshold setting in the traditional solution are mainly based on human experience. However, when environmental noise is close to the arc spectrum characteristics, the arc spectrum characteristics cannot be effectively distinguished, which may result in false alarm. In addition, in parallel and

ground arc detection, the noise floor varies in different environments, meaning that current technology cannot effectively identify arcs.

(2) Scenario adaptability

With the technological development and product evolution of PV modules and PV inverters, the current of PV modules and power of a single inverter are continuously increased. In actual application scenarios, the input cable length and maximum arc current may exceed the test conditions specified in current standards. For example, for the 100 kW inverter solution design, the input power cable may be longer than 200 m, and the maximum current of a single MPPT may exceed 26 A. As shown in Figure 2-3, the arc characteristic signal gradually weakens as the current and cable length increases, posing higher requirements on the precision of the detection instrument and algorithm.

2.3 Technical Features of Huawei AFCI Solution

By leveraging its advantages and experience accumulated in other fields, Huawei has proposed its AI BOOST AFCI intelligent arc detection solution to solve the preceding difficulties. The solution features the following highlights:

- (1) Combines AFCI and deep learning technologies based on Huawei technical experience in the ICT and AI fields. Unlike manual induction design, AI is based on a highly nonlinear model, and simultaneously calculates and iterates massive data to find high-dimensional feature rules that effectively distinguish characteristic signals with similar forms, as shown in the following figure.
- (2) Uses AI and deep learning technologies to enable the detection model to continuously learn unknown spectrums, effectively improving noise adaptability. In addition, the model generalization capability has

improved so the model can effectively identify arc characteristics in different scenarios, improving scenario adaptability. Figure 2-6 shows the logical block diagram of Huawei solution. Table 2-1 compares the traditional AFCI solution and Huawei intelligent solution.

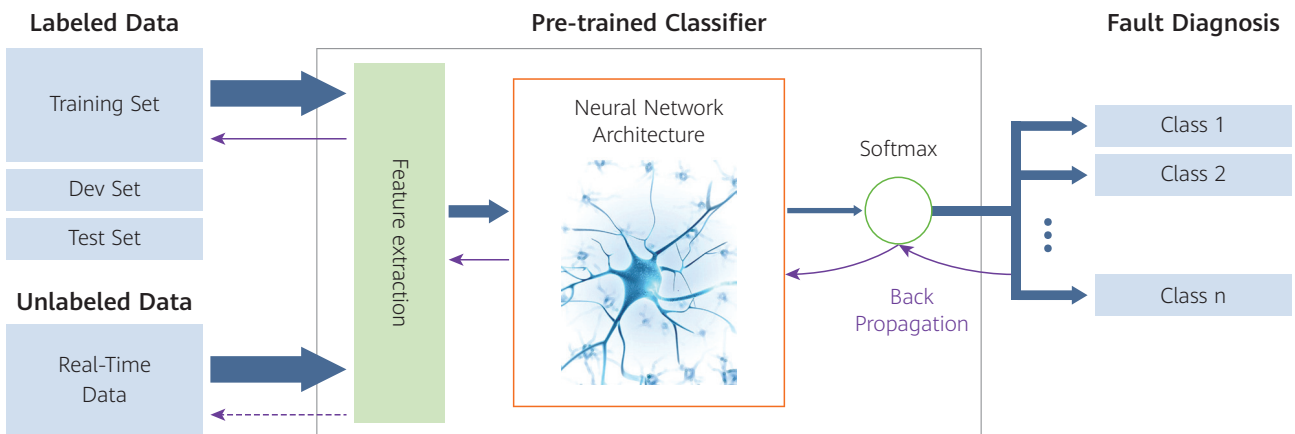
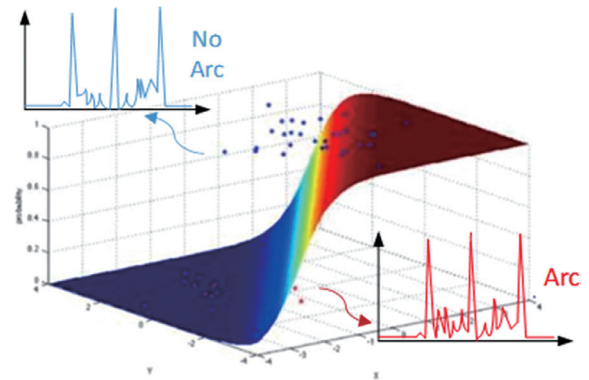


Figure 2-6 Logical block diagram of the AI solution

Table 2-1 Traditional arc detection solution vs. Huawei AI BOOST AFCI intelligent arc detection solution

Item	Traditional Solution	Huawei's Solution
Noise adaptability	<ul style="list-style-type: none"> Likely to raise false alarms for signals with similar characteristics 	<ul style="list-style-type: none"> Can effectively distinguish between noise and arc characteristics Can avoid false alarm and missed alarm completely
Scenario adaptability	<ul style="list-style-type: none"> Supports only the input cable length (61 m) required by the certification Supports only the input current (14 A) required by the certification 	<ul style="list-style-type: none"> Supports the maximum input cable length of 200 m Supports the maximum input current of 26 A supports module-level arc fault locating when system is fully-equipped with optimizers

03

AFCI Technology Verification and Evaluation Results



To better understand the status and performance of Huawei inverters with the AFCI function, CGC, as entrusted by Huawei, established a verification team to

comprehensively evaluate the AFCI technology used by Huawei from February to May 2020. Figure 3-1 shows the technical verification and evaluation process and items.

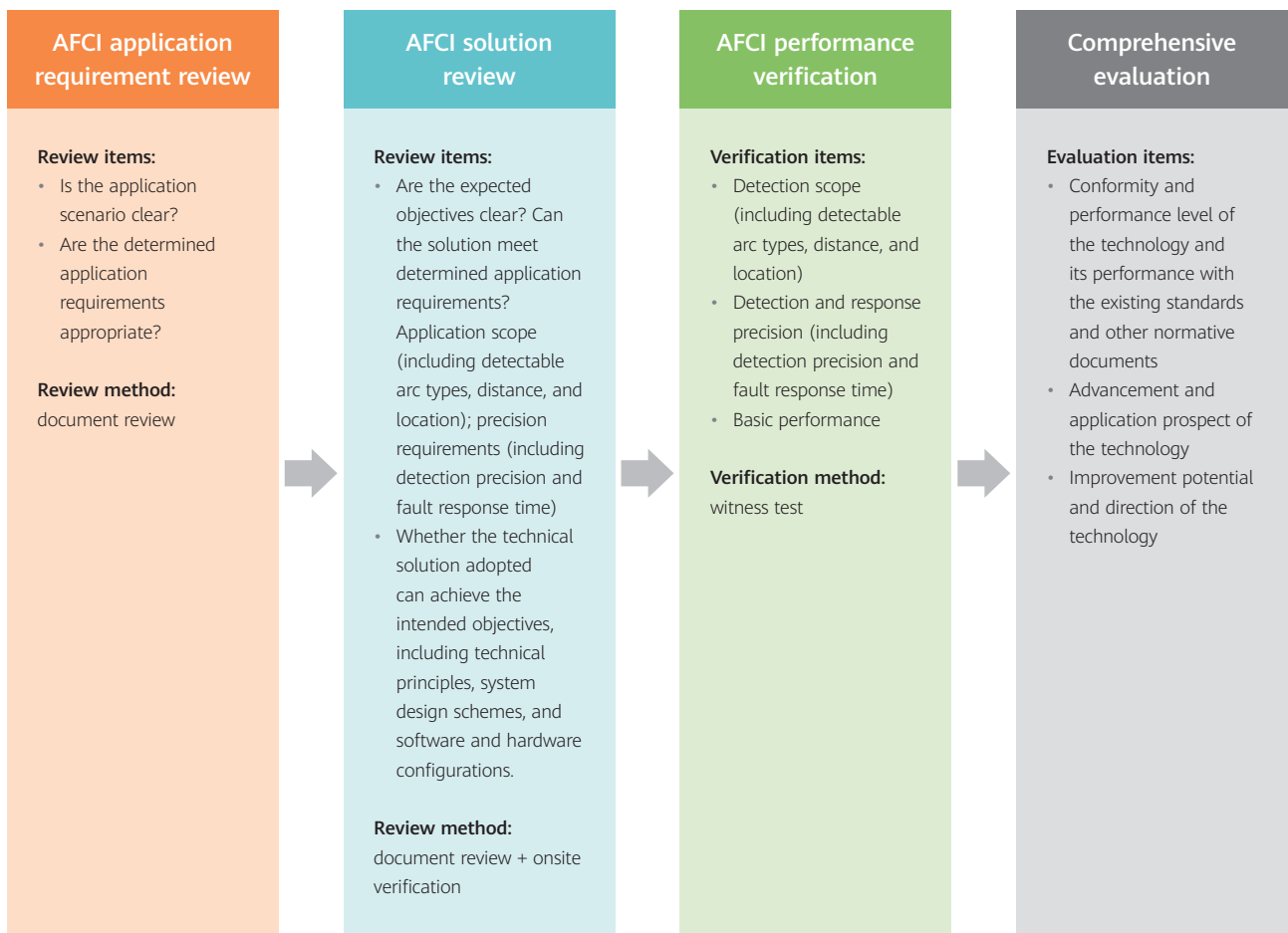


Figure 3-1 Technical verification and evaluation process and items

3.1 Application Requirements and Technical Solution Review

In terms of application scope, Huawei focuses on distributed (including residential) PV systems for AFCI application.

Based on the occurrence probability of the three types of DC arcs, as well as the difficulties and applications of AFCI technologies, Huawei focuses its technological development on the detection of series arcs.

Based on the application scope, Huawei determines the technical indicators and system solutions for AFCI. For

details, see chapter 2.

Upon the review's completion, the verification team concluded that AFCI technology used by Huawei meets the application requirements and technical principles, design, and system configuration solutions to fulfill the expected functional requirements and preset indicator requirements. The exclusive AI BOOST AFCI intelligent arc detection solution effectively resolves difficulties that arise due to noise and scenario adaptability.

3.2 Performance Verification

Currently, many countries and regions have formulated or determined the standards for arc detection and shutdown of distributed rooftop PV systems. These standards include UL 1699B and NEC 2017 690, adopted by the US and Canada,

and IEC 63027, led by Europe and the IEC. UL 1699B-2018 "Photovoltaic (PV) DC Arc-Fault Circuit Protection" is the mostly widely used standard, while IEC 63027 is still being drafted. Table 3-1 lists the main parameters specified in these standards.

Table 3-1 Performance requirements of UL 1699B and IEC 63027 (draft)

Item	UL 1699B - 2011	UL 1699B - 2018	IEC 63027
Arc type	Series arc or series/parallel arc (no mandatory requirements)	Series arc	Series arc
Cable length	61 m	50 μH + 0.7 μH per meter above 80 meters	50 μH
Capacitance to ground	-	±1 nF	±1 nF
Protection threshold	Arc duration < 2s; arc energy < 750 J	Arc duration < 2.5s; arc energy < 750 J	Arc duration < 2.5s; arc energy < 750 J
Fault clearing	Manually cleared	<ol style="list-style-type: none"> Automatically cleared after a delay of 5 minutes; Manually cleared; Manual clearing required if more than five arc faults occur within 24 hours 	<ol style="list-style-type: none"> The protection device should reset automatically 3 minutes after action. When the protection device needs to reset for the second time, the automatic reset waiting time should be at least 10 minutes. If the protection device automatically has reset five times in a day, the next reset must be performed manually.

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Item	UL 1699B - 2011	UL 1699B - 2018	IEC 63027
Fault location	Input side	Both input side and between PV modules	Both input side and between PV modules

Based on existing standards, CGC — together with Huawei and other related parties — developed the CGC/GF 175:2020 "Technical Specifications for Arc Detection and Rapid Shutdown Performance Evaluation." This specification covers the requirements of the UL 1699B-2018 standard and poses higher requirements, with the status quo

of distributed PV and future technology development considered, including rating evaluation requirements. Table 3-2 describes the rating evaluation requirements for AFCI core performance in CGC/GF 175:2020 "Technical Specifications for Arc Detection and Rapid Shutdown Performance Level Evaluation."

Table 3-2 AFCI core performance rating evaluation requirements

Requirements Level Item	L1	L2	L3	L4	L5
Types of arcs that can be detected	Series arc	Series arc	Series arc	Series arc	Reserved for detection scope extension
Supported fault detection scope	Input side	Input side, between PV modules, and output side	Input side, between PV modules, and output side	Input side, between PV modules, and output side	
Supported system types	With or without optimizers	With or without optimizers	With or without optimizers	With or without optimizers	
Arc fault location	Cannot be located	Cannot be located	Cannot be located	Can be located	
Supported cable length	61 m	80 m	80 m (single-phase) 200 m (three-phase)	80 m (single-phase) 200 m (three-phase)	
Supported maximum arc current	0.9 x I _{max}	0.9 x I _{max}	0.9 x I _{max}	I _{max}	
Arc-generated energy	750 J	650 J	600 J	500 J	
Shutdown time	2.5s	2.0s	1.5s	0.5s	
Arc detection accuracy	100%	100%	100%	100%	
Technical requirements	PV string detection	Optimizer system + 1% independent CT	>200 DMIPS (Dhrystone 2.1) high-performance CPU + 0.5% independent CT	>200 DMIPS (Dhrystone 2.1) high-performance CPU + 0.5% independent CT	

According to the CGC/GF 175: 2020 "Technical Specifications for Arc Detection and Rapid Shutdown Performance Evaluation," the verification team performed onsite tests

and verification for Huawei inverters with the AFCI function based on the items listed in Table 3-2. Table 3-3 provides the verification results for each item.

Table 3-3 Huawei AFCI performance test and verification results

Item	Result
Types of arcs that can be detected	Series arc
Supported fault detection scope	Input side, between PV modules, and output side
Supported system types	Applicable with optimizers
Arc fault location	Can be located
Supported cable length	80 m (single-phase) 200 m (three-phase)
Supported maximum arc current	I _{max}
Arc detection accuracy	100%
Arc-generated energy	< 500 J
Shutdown time	0.5s
Technical requirements	>200 DMIPS (Dhrystone 2.1) high-performance CPU + 0.5% independent CT + module-level arc fault locating

Based on the test and verification results, the AFCI function integrated into Huawei inverters achieves the following:

- (1) Complies with the UL 1699B-2018 standard.
- (2) Reaches the L4 level in CGC/GF 175: 2020 in terms of AFCI core performance.

3.3 Comprehensive Evaluation



Huawei inverters with the AFCI function have been successfully applied in many countries and regions, such as China, North America, Europe, Asia Pacific, Latin America, Southeast Asia, the Middle East, and Africa.

Based on the technical review and performance verification results, it can be concluded that the AFCI function integrated into Huawei inverters achieves the following:

- (1) Complies with the UL 1699B-2018 standard and reaches the L4 level in CGC/GF 175:2020.

- (2) Features mature series arc detection and rapid shutdown technologies, which can be used to effectively prevent arc hazards in the rooftop PV system with complex environment.
- (3) Delivers module-level precise arc fault location when optimizers are fully configured.
- (4) Implements high-precision detection in a wider scope (for example, when the cable length exceeds 200 m or the current exceeds I_{max}) with the AI BOOST AFCI intelligent detection solution based on existing performance levels.

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