01. BACKGROUND

According to relevant data, the global photovoltaic installed capacity was approximately 240GW in 2022, with a cumulative installed capacity of 1.2TW worldwide. As one of the core devices in the photovoltaic system, the inverter is constantly undergoing technological upgrades and innovations with the continuous maturity and development of the photovoltaic market. As an important trend in the development of inverter technology, the reliability has a crucial impact on the power generation and safety of the photovoltaic system.

The DC arcing seriously affects the safety of the power plant during the operation of the photovoltaic system and is receiving increasing attention in the practical applications. The statistical data indicates that most photovoltaic fire accidents in power plants are caused by DC arcing.

In many cases of fire accidents in photovoltaic installations, overheating, DC arcing, and electrical fault are main causes. This further proves that it's crucial to strengthen the safety monitoring and protection of DC arcing in the photovoltaic system.

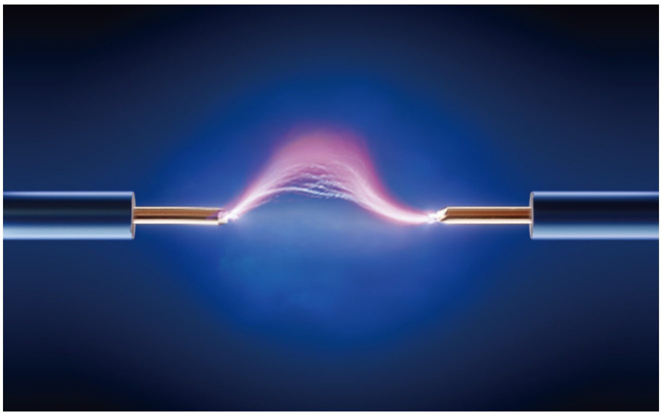
At present, there is no unified solution or regulatory policy for the regulation and standard formulation of DC arcing fault test in the photovoltaic system worldwide. The United States is the earliest country to initiate the study and formulation of the standards for the fire issue of the photovoltaic system. The UL Outline standard was issued by UL for the first time in 2011 and updated many times. The latest version is UL 1699B-2018. This standard specifies the test requirements and performance indicators of arc fault protection devices (AFCI) in PV systems. The National Electrical Code (NEC) 2017 edition first introduced the requirements for AFCI, stipulating that AFCI devices complying with UL 1699B standard shall be installed in DC circuits of photovoltaic systems. In addition, the PV installation specifications in several European countries have gradually increased the requirements for the introduction of AFCI with reference to IEC 63027. With the increasing attention paid to the operational safety of the photovoltaic system, the test and protection technology for DC arcing fault in the photovoltaic system has become an urgent issue to be solved.

Therefore, developing an effective DC arcing test solution to protect the inverter and improve its reliability and safety has become one of the current hot research fields.

02. THEORETICAL ANALYSIS

2.1 Formation Mechanism

The electric arc refers to a glowing phenomenon which is generated by the air ionization discharge arising from the air breakdown by the voltage between conductors when distance between charged conductors is relatively close. When the DC current outputted by the photovoltaic module is momentarily switched off in a photovoltaic system, such as the disconnection of the switches, damage to the components and virtual connection of the connectors, the high voltage between the conductors may cause arcing.

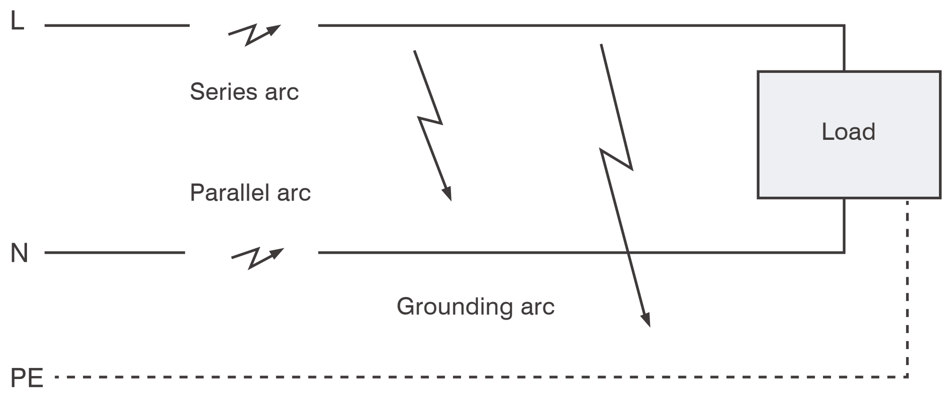


Arcing Generation

Although the conductors are disconnected at this point, the current will continue to flow through the arcing between the conductors. Due to the characteristic of constant current for the DC side, it is difficult to eliminate the arcing after generated. The arcing will disappear automatically only when the distance of the separated conductors is long enough, or the electric arc in the current circuit is eliminated. The effective solution for DC arcing in the industry is to eliminate the circuit current.

2.2 Arcing Classification

As shown in the figure below, the arcing in the photovoltaic system can be divided into three types: series arcing, parallel arcing and grounding arcing.



Arcing Classification

- **Series Arcing**

  The arcing in DC wires with the current flowing through it, usually due to a small distance caused by loose connectors.

- **Parallel Arcing**

  The arcing between phase and neutral wires or between phase wires due to conductor insulation damage or other reasons, mostly caused by damaged cable.

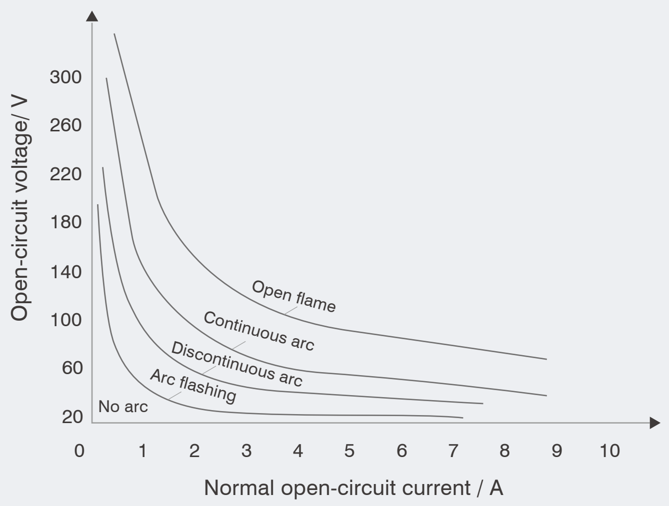
- **Grounding Arcing**

  The arcing caused by the insulation fault of high-voltage between the phase wire and the ground, grounded metal or equipment enclosure.

Photovoltaic systems have some inherent characteristics that make series DC arcs more prone to occur such as high DC voltage, complex circuits, outdoor installation environments, etc.

The formation of photovoltaic DC arc often has the following characteristics:

- The arc is a high-power discharge phenomenon. Accompanied by the arc, a large amount of electric energy is converted into the thermal energy, resulting in the extremely high temperature at the arc.
- The arc is a self-maintained discharge phenomenon, it can maintain stable combustion for a considerable period without extinguishing at a non-high voltage and non-high current.
- The arc is a plasma with extremely light weight. The flow of gas in the arc area, including the natural convection and the magnetic field generated by the external environment, and even the arc current itself, may cause the arc to be subjected to force and reshaped thereby.
- The arc strength increases with the increase of voltage, current and spacing, while the stability decreases with the increase of spacing. The arc characteristic curve is as shown in the figure below.



Arc Characteristic Curve

Most of the current distributed photovoltaic systems are designed based on 1000V-1100V, with mainstream 182/210mm high current modules generally selected, all of which operate at the current of over 14A. Therefore, once the arcing is generated, it is highly likely to cause an open flame and lead to the occurrence of a fire.

2.3 Related Standards

Currently, the major international standards for AFCI in PV systems include:

- **UL 1699B Standard:** The UL Outline standard was issued by UL for the first time in 2011 and updated many times. The latest version is UL 1699B-2018. This standard specifies the test requirements and performance indicators of arc fault protection devices (AFCI) in PV systems.

- **IEC 63027 Standard:** An international standard developed by the International Electrotechnical Commission (IEC) for the first time in 2017, specifying the end performance requirements for AFCI in PV power generation systems.

- **AS/NZS 5033 Standard:** The AFCI standard issued by Australia and New Zealand for the first time in 2019 AS/NZS 5033:2019, specifying the functional requirements and test methods for AFCI in PV systems.

- **NEC 2017 Section 690.11:** The National Electrical Code (NEC) 2017 edition first introduced the requirements for AFCI, stipulating that AFCI devices complying with UL 1699B standard shall be installed in DC circuits of photovoltaic systems.

- **CSA C22.2 No. 293 Standard:** A safety standard for photovoltaic systems issued by CSA Group of Canada. Since the 2019 edition, it has incorporated the functional requirements and test provisions of AFCI and requires reference to the UL 1699B standard.

In addition, the PV installation specifications in several European countries have gradually increased the requirements for the introduction of AFCI with reference to IEC 63027.

In summary, UL 1699B and IEC 63027 standards are currently two major international standards for AFCI detection and protection. They have high consistency in the definition of AFCI functions, technical requirements, test methods, etc. Standards in other countries and regions mostly refer to or reference these two major standards. This helps to facilitate the interoperability and internationalization of AFCI technology and products.

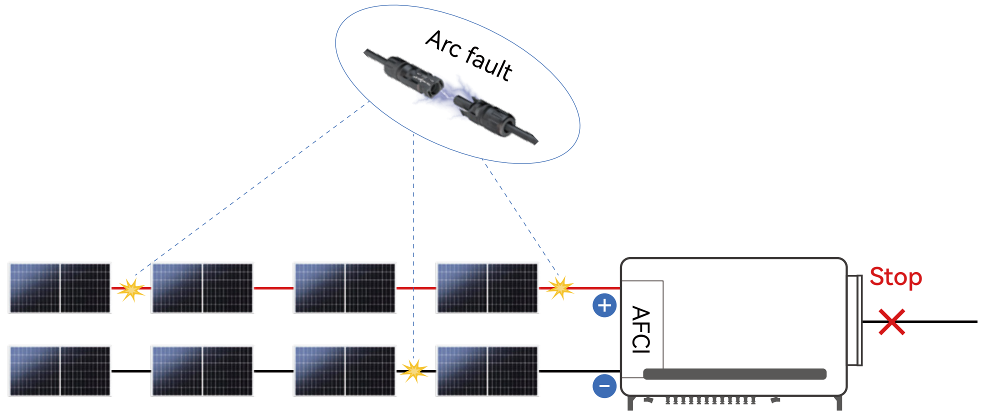
The specific requirements for key parameters vary in different AFCI standards. In comparison, UL 1699 standard has the most stringent and detailed requirements for AFCI performance and technology. IEC 63027 basically adopts the UL 1699 regulations but slightly relaxes some specific numerical requirements. The AS/NZS 5033 standard mainly refers to UL 1699 for some technical requirements but does not require high-end product levels and focuses more on basic AFCI products. Some key parameters in UL1699B are as follow:

Item	UL 1699B: 2021
Test distance	80m: including the maximum length of wiring between photovoltaic modules and DC cables
Protection duration	$<2.5S$
Arc energy	$<750J$
Arcing position	Wire terminal, between wires
Max. arc current	$\geq 16A$

In general, all these requirements do propose higher benchmarks for key functions of AFCI, such as response speed, detection sensitivity, and protection range, which help to improve AFCI technology and optimize product performance in the industry.

03. SOLUTION

When damage (to module frame, cables, connectors etc.) and arcing occurs at any position of the DC-side, according to Joule's law, the thermal effect of a short-circuit point is in direct proportion to the square of the current, greater current thus increases the fire risk. Therefore, one of the methods in which the risk of fire can be effectively reduced is to disconnect the DC current, by disconnecting the inverter AC side and stopping the DC to AC current conversion and thus the current injection on the DC side.



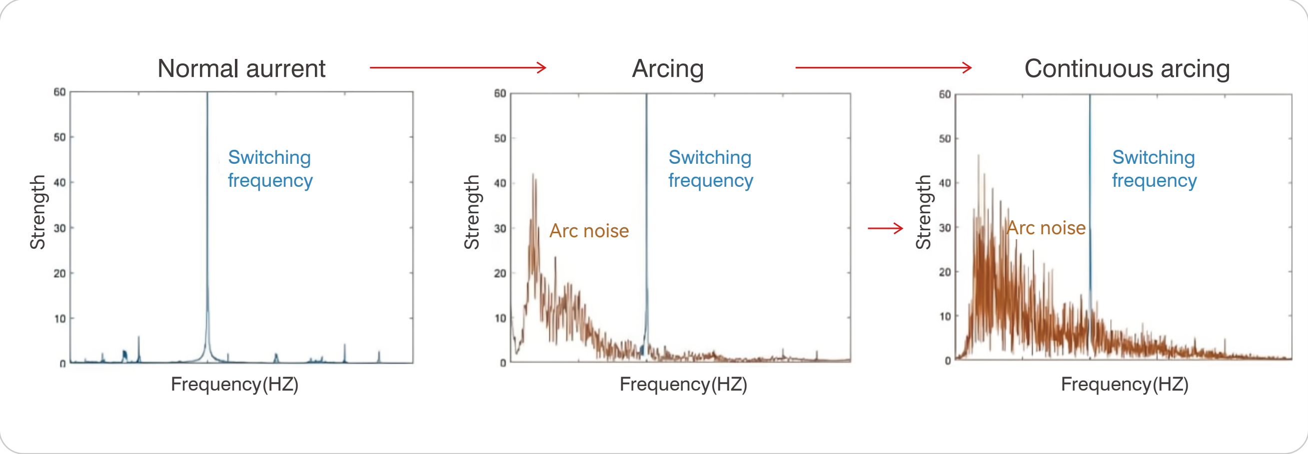
DC Arcing Protection Function of Inverter

3.1 How to Identify an Arc Fault?

Consequently, the key for the DC arcing test protection function is to identify the arcing current and timely switch off the current injection at the DC side.

Essentially, arcing occurs when gas suffers from electrical breakdown due to the strong electric field between conductors to form continuous plasma and generate very bright ultraviolet radiation and strong heat. The arcing generation mechanism and positions are different in the photovoltaic system, so the arcing current is generally identified by measuring the current at the DC side and using the spectral analysis method.

The plasma is in a disorderly state due to the ionization of the air during the arcing, and the current flowing through the arc will have strong fluctuations. This highly volatile current on the spectrogram shows a very wide noise band, which is the so-called "white noise" in the spectrum analysis, while the normal DC current without interference shows a relatively stable state. As shown in the figure below, the DC spectrum only shows the switching frequency of the inverter when there is no arcing. However, a certain "noise frequency" will appear when arcing begins, and the more disorderly noise frequency will be generated during the continuous arcing.



Arc Spectrogram

After the DC arcing protection function of the inverter is enabled, the inverter will test the input current of each string in real time. After the characteristic current phenomenon of the arc (as shown in the figure above) is tested, the inverter will immediately switch off the AC side and report an error. The current circuit at the DC side will be switched off and the arc will be eliminated when the AC current is switched off.

3.2 Technical Characteristics

GoodWe focuses on the safety issues of the power plant and continuously improves AFCI technology, including algorithms and test accuracy, etc. After several technological changes, a breakthrough progress has been made in DC arcing test technology, and the new AFCI technology has now been launched.

AI Integrated Deep Learning

Different from the traditional solution where the arc testing algorithms and threshold settings are mainly based on personal experience, GoodWe AFCI calculates and iterates the massive data, continuously learns the arc characteristics, and forms a unique arc characteristics library to eliminate false and omitted reports caused by environmental noise. The AI integrates the deep learning to enable the test model to continuously learn the unknown spectra and adapt to various application scenarios thereby.

Powerful Data Acquisition Capability

With a special arcing sensor, the GoodWe AFCI has the powerful data acquisition capability to continuously search for the arc characteristics. Once the arc is found, it will timely report to the chip.

Strong Adaptability and Flexibility

It meets the requirements for the cable length and input current of high-current modules for larger photovoltaic installations, quickly switches off the power supply within milliseconds, which is far better compared to the UL 1699B.

04. PERFORMANCE VERIFICATION

To accurately evaluate the performance level of GoodWe AFCI technology, TÜV Rheinland established a verification team to conduct a comprehensive validation and evaluation of related technologies under the commission by GoodWe. The evaluation process flow is as shown.

01 Evaluation of AFCI Application Demands

- **Evaluation contents:** Evaluate whether the application scenarios are comprehensive and whether the application demands of each scenario are appropriate and meet the requirements.
- **Evaluation method:** Document evaluation.

02 Evaluation of AFCI

- **Evaluation contents:** Evaluate whether the technical solution meets the expected scenario requirements and whether the performance indicators have the technical advancement.
- **Evaluation method:** Document evaluation + test and verification by the laboratory.

03 Verification of AFCI Performance

- **Verification contents:** Arcing test distance, maximum input current, arc energy, switching-off time; maximum operating current.
- **Verification method:** Laboratory and on-site witness, test and verification.

04 Comprehensive Evaluation

- **Verification contents:** Arcing test distance, maximum input current, arc energy, switching-off time; maximum operating current.
- **Verification method:** Laboratory and on-site witness, test and verification.

Evaluation of Application Demands and Technical Solutions

GoodWe mainly applies the AFCI technology to residential and C&I photovoltaic power generation system products, with clear application scenarios and application demand for related scenarios in policies and standards.

Therefore, GoodWe has proposed corresponding technical indicators and developed solutions as described in Section 3 above. Through the review, the verification team has made the following conclusion: The technical solutions proposed by GoodWe exceeds the technical market standard to deal with DC arc faults. The AFCI solution developed by GoodWe provides sufficient hardware and software support for the realization of the proposed technical indicators, and will be tested and verified in the next test and verification phase.

Performance Verification

Based on the technical indicators developed by GoodWe and the safety classification evaluation requirements aforesaid, the verification team has established the laboratory and on-site test solution with reference to the existing international standards.

4.1 AFCI Test and Verification Solution

Test serial No.	Minimum Iarc (A)	Impp (A)	Vmpp (V)	Voc (V)	Clearance (mm)
1	2.5	3.0	312.0	480.0	0.8
2	7.0	8.0	318.0	490.0	0.8
3	14.0	16.0	318.0	490.0	1.1
4	7.0	8.5	607.0	810.0	2.5
5	18	30.0	318.0	490.0	1.1

Notes:
1. The series arcing is simulated at three points: the starting point of the PV input positive electrode, the middle position of the component and the end of the PV input negative electrode in each test;
2. The characteristics of two types of frame technology modules are simulated at each testing point for testing;
3. All tests are carried out in the analog line with the length of 200 m;
4. The tests above are carried out on two types of inverters with AFCI function: DNS G3 (residential single-phase series inverter) and SMT US (commercial three-phase series inverter), respectively, simulating residential and commercial application scenarios. The test serial number 5 is only conducted on SMT US series;
5. The tests above are completed in the laboratory using the testing equipment such as photovoltaic array simulator, coupling network, line simulation network and arc generator.

According to the test solution above, the test verification results are as follows through multiple repeated tests:

AFCI Performance Test and Verification Result

Performance indicator	Result
Test arc type	DC series arc
Arc test range	PV input, output ends and middle of modules
Max. test cable length	200m
Max. input current	30A
Arc test energy	<300J
Shut-down time	<500ms
Arc test accuracy	100%

4.2 Comprehensive Evaluation

Based on the results of the technical evaluation and test, the following comprehensive conclusion can be made:

1. GoodWe's AFCI technology has technical advancement, superior indicators and reliable and stable performance in the actual test,
2. The AFCI meets the performance indicator requirements of current mainstream standards such as US NEC 2020 and UL1699B, with some indicators exceeding the standard requirements,
3. GoodWe's photovoltaic string inverter integrated with the AFCI function can effectively prevent arc hazards and related fires, and reduce property losses.

05. CONCLUSION

The above discussion indicates that photovoltaic systems are being more intelligent, digital and secure. Through the study of the European standard (IEC 63027) and relevant international standards, DC arcing test technology is a key technology to ensure the safety of the photovoltaic system. The photovoltaic system manufacturers, installers, and regulatory agencies in other regions than the United States and Europe shall also work closely together to draft and comply with relevant standards and specifications to ensure that the photovoltaic systems meet the highest safety standards during design, installation and operation.

With the continuous development and expansion of photovoltaic technology, DC arc test technology continue to evolve and be innovated. We hope that this paper will play a positive role in propelling the safe development of photovoltaic systems and promoting the industrial cooperation and knowledge sharing. Through collaborative efforts, we are confident in establishing a more reliable, safe, and sustainable photovoltaic system, thereby making our contributions to the future of the clean energy.