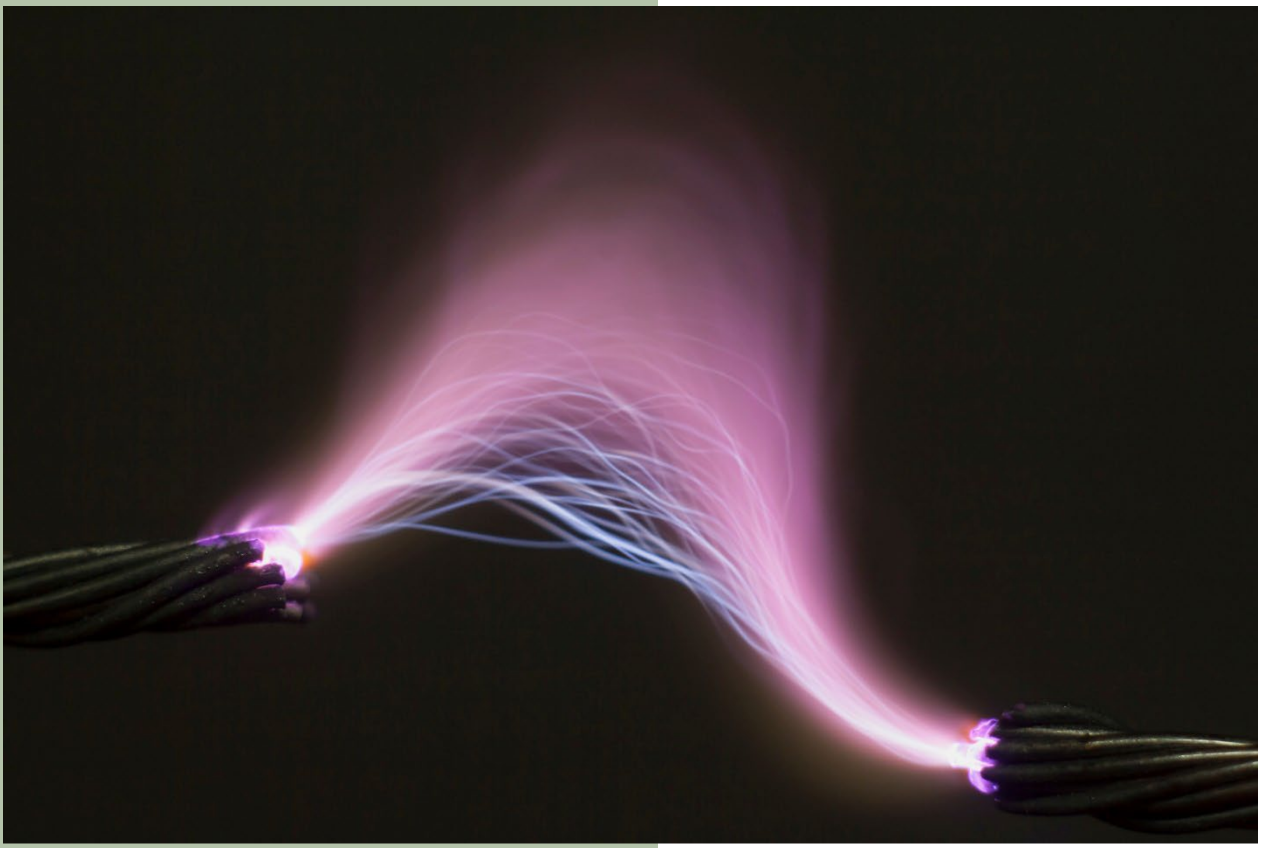

Arc Fault Protection in PV systems

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Business Unit Solar Energy

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1 Introduction

Today, PV systems have become very safe. Features like RCMU (residual current monitoring unit), DC disconnector, and isolation monitoring have contributed to achieving a very high level of safety. Nevertheless, fire safety of PV systems is still a highly debated topic within the solar industry.

When discussing this subject, a fundamental distinction must be made between:

- the **risk of fire** (probability that a fire occurs), and
- the **risk for emergency responders** (probability of a firefighter becoming injured during a fire).

The **second risk** is strictly related and **consequential to the first risk**, that is: the risk for rescue personnel only exists after a fire has already occurred. That is why by reducing the risk of fire, the risk for emergency responders is automatically reduced.

In Germany, one of the largest PV markets with more than 2 million PV systems installed, over the last 20 years, PV fires have occurred in 0.006% of all installations [1]. This means that, statistically, **99.994%** of PV installations are **not causing a fire**. Similar numbers were reported from the UK market [2].

So, whenever we are talking about PV fire safety, we should keep in mind that we are talking about the 0.006% PV systems that are statistically "at risk". That is: 1 in every 17,000 installations.

In order **to further reduce the risk of fire**, and to further lower the number of affected systems, **additional** safety **measures** may be considered including:

- installation measures (e.g., ensuring adequate ventilation, avoiding accumulation of flammable materials, and properly installing conductors and connectors [3]), or
- measures based on technical equipment, such as earth fault and arc fault protection devices.

However, since the percentage of statistically safe systems is already very high, extra care must be taken when selecting additional measures, to ensure that they do not have a negative impact on other aspects of safety. **Arc fault protection** is a good example of a safety measure that effectively **reduces the risk of fire**, **without compromising other safety aspects**.

2 Arcs in PV systems

In the 0.006% of systems that are at risk of causing a fire, the root cause is attributed to electric arcs on the DC side of a PV system.

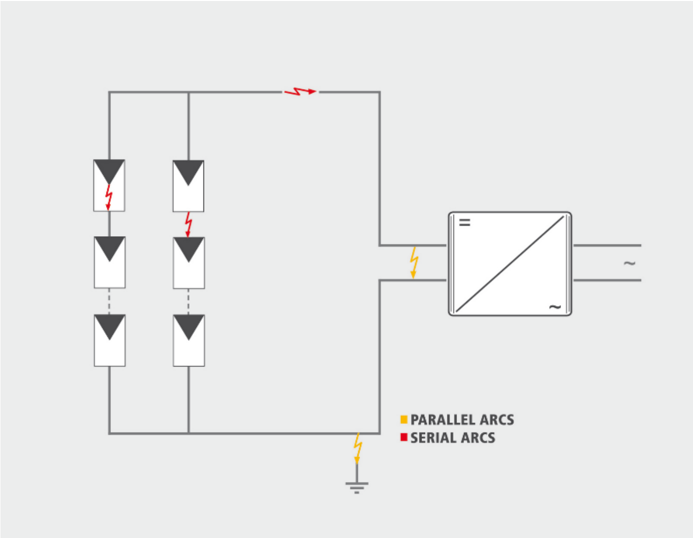

Figure 1: Series and parallel arcs in PV systems

There are 2 types of DC arcs (Figure 1):

1. **Parallel arcs**: these can occur as a consequence of damaged cable insulation, which can result in a short-circuit between DC+ and DC-, or from DC+/DC- to ground. However, parallel arcs are very unlikely, especially in ungrounded PV systems used in Europe: for a parallel arc between 2 DC cables to occur, the insulation would need to be damaged at the same point and at the same time, whereas in the case of a double short-circuit to ground, the inverter-integrated insulation monitor would detect the 1st short circuit to ground first.

2. **Serial arcs**: these are related to **connection points** (e.g., in module junction boxes, DC connectors, combiner boxes, terminals of DC switches and inverters, etc..), and they can form when there is a poor or deteriorated connection, that eventually becomes interrupted. This can be caused by a variety of factors, including aging or long-time weathering of contacts and connections, mechanical damage to connectors, poor maintenance, screw terminals insufficiently tightened, and poor installation of DC connectors (e.g., improper insertion, poor crimping, or mismatching). In such situations, the contact area of the connection is reduced, and there is a higher contact resistance. This leads to increased heat loss and a higher temperature in the connection, which in turn accelerates the deterioration process further (Figure 2).

Eventually, the conductor continuity will be interrupted, and a very small air gap will form. If the electric field is strong enough (> 3kV/mm [4]), air will ionize and produce a conductive plasma (what we define as an arc), allowing current to flow through the air gap.

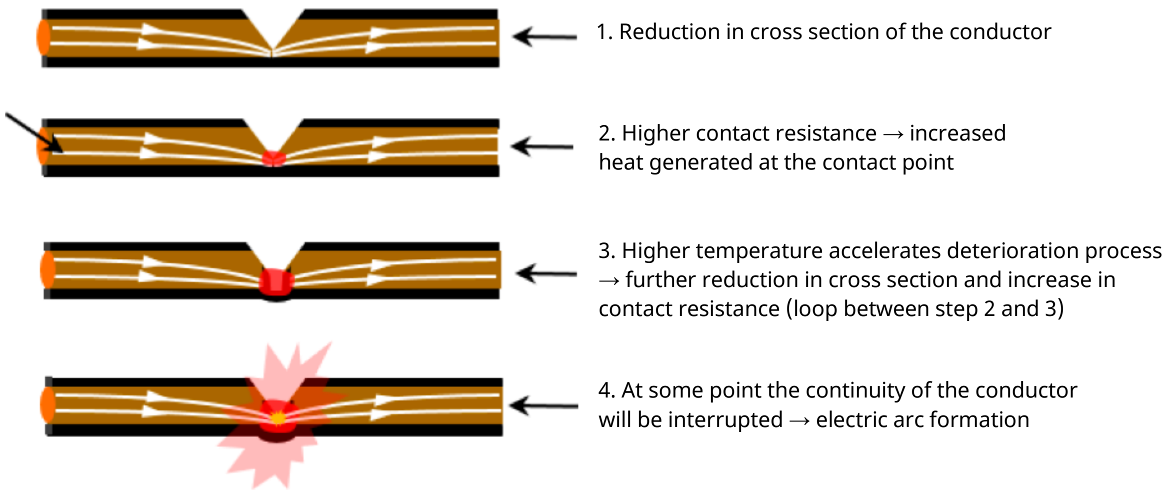

Figure 2: Arc formation process inside a conductor [12]

A burning electric arc can reach temperatures above 10,000 K [5] (which can ignite nearby combustible material, and initiate a fire), and emits both visible and UV light.

The first level of protection against DC arcs that should always be observed, is to **minimize the number of connection points**, in order to minimize the risk of arcs in the first place. This can be considered a "passive" protective measure, as it is a measure that is intrinsic to the way in which the system is designed and installed [6]. Only when this risk-minimization measure has been observed, does it make sense to implement additional and “active” risk-mitigation measures.

3 DC arc detection and interruption in PV systems

When it comes to the root cause of fire, among the (relatively low) number of PV fires, serial arcs have a much higher share compared to parallel arcs, due to the large number of contact points on the DC side of PV systems. Therefore, technology as well as standards for arc fault detection have been the focus of serial arcs. Also, detectors for AC arcs cannot be used to detect DC arcs, because of their differing characteristics (for DC currents there is no zero-crossing), therefore a specific technology is needed to detect DC arcs.

A variety of techniques for detecting and interrupting arcs in PV systems have been developed over the past decade [7, 8, 9], but spectral arc detection is the most mature and widely adopted technology within the industry. This is based on the analysis of the voltage and current signals caused by the arc in the frequency domain.

When a serial arc occurs, the voltage and current signals of the PV system are significantly affected (Figure 3). During normal operation, the AC component of the signals in the time domain is very small. When an arc occurs, the signals are very unstable with peaks and high rates of change. The signal can be converted and analyzed in the frequency domain through an FFT (Fast Fourier Transform). Here, the noise introduced by the arc can be seen by the higher amplitude of the frequency components, which increase the overall "noise floor" of the system, compared to normal conditions without an arc (Figure 4). Basic detection techniques compare measured values of current and voltage signal with defined threshold values, to determine whether the system is in an arc or non-arc condition.

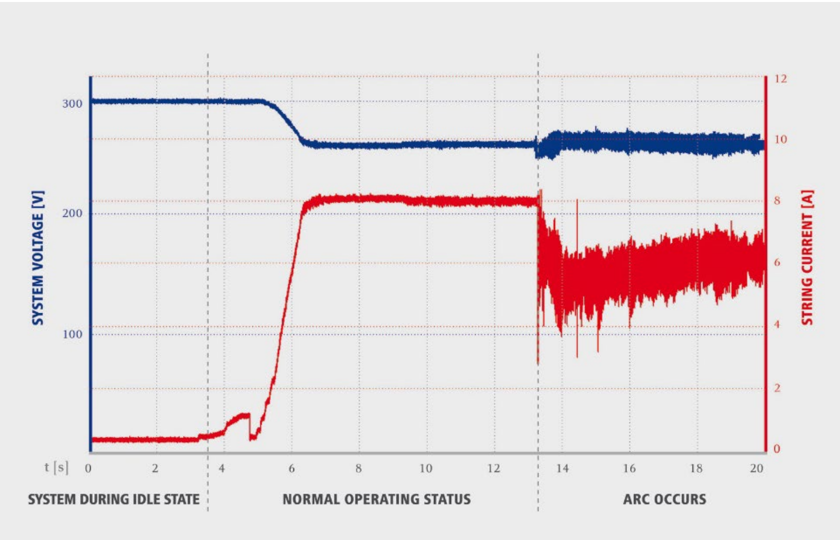

Figure 3: Voltage and current signal in a PV system in the time domain, before and during an arc

However, determining when the system is experiencing an arc is not straightforward and has several challenges [7, 9], for example:

- the inverter itself creates noise peaks at certain frequencies (depending on the inverter) that can overlap with the arc signature, as can be seen in Figure 4.
- the switching frequency of other powered electronic devices including charge controllers and DC/DC converters, as well as the presence of other electronic devices (within or close to the PV array) can introduce additional noise.
- long PV cables can behave as antenna, by adding noise in the frequency band between 100 kHz and 500 MHz. PV cables can also act as a low pass filter, due to their inductive component, therefore attenuating arc noise at high frequencies, and making an arc harder to be detected.
- for frequencies below 1 kHz, current steps and variations, caused for example, by inverter switch-off, power adjustments or environmental conditions including fast moving clouds or vibrations caused by wind, can cause the current signal to look like an arc.

All these sources of interference can create **2 types of issues** for the arc fault detector:

- the extra noise can overlap with the arc signal ("**masking**"), and the arc can persist without being detected, or
- the extra noise can be interpreted as a real arc ("noise or **false tripping**"), and the inverter can trip even if no real arc is occurring, therefore interrupting power generation.

The issue of masking is a safety-related one, while false tripping is more related to performance and cost, because of the unwanted system downtime. A proper and robust arc detector should be able to manage these challenges, and detect arcs with high reliability and accuracy, while at the same time minimizing the risk of false trips [10].

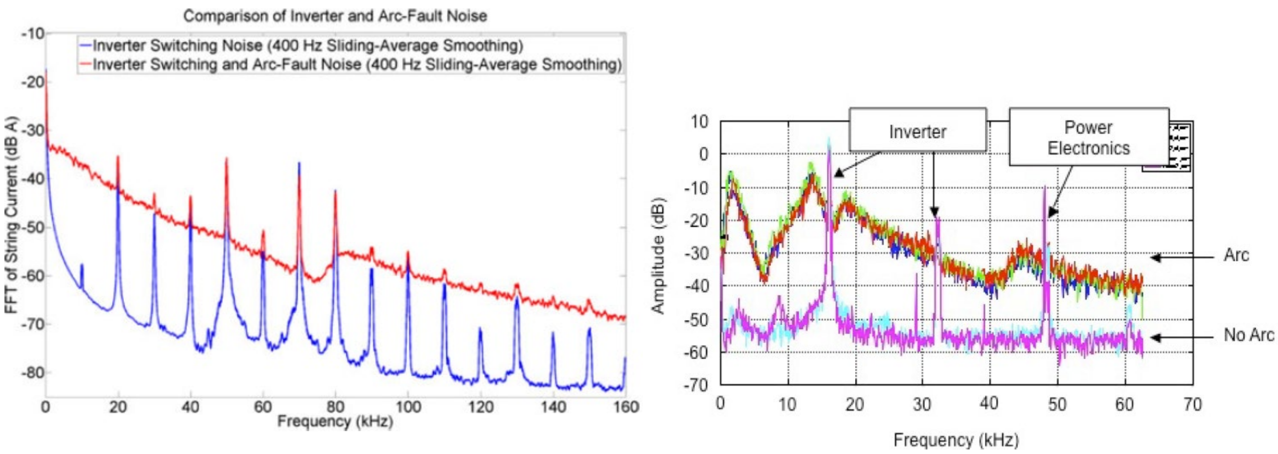

Figure 4: Examples of frequency spectrum with (red curves) and without (blue/purple curves) an arc [8, 10]

4 Standards for PV arc fault protection

The first standardization occurred in 2011 in the US with the **UL1699B**, which first introduced the name "AFCI" (Arc-Fault Circuit Interrupter) by which the technology is commonly known. On an international level, there is also an IEC standard **(IEC 63027)**, that uses a somewhat different terminology: an "AFD" (Arc-Fault Detector) is the device that monitors the AC signals in the DC wiring and detects arcs, while an "AFI" (Arc-Fault Interrupter) is the device that actually breaks the circuit, after receiving the command by the AFD upon detection of an arc. The combination of AFD and AFI forms what is known as "**AFPE**" (**Arc-Fault Protection Equipment**). This can be either a separate device or integrated in the inverter.

The IEC 63027 requires testing of the AFPE under different arcing conditions, including different arc currents, open circuit voltage and mpp voltage, different arc gaps and separation rates of the electrodes of the arc generator. The arc needs to be detected within 2.5 seconds, or before the arc energy exceeds 750 J, whichever occurs first (Figure 5).

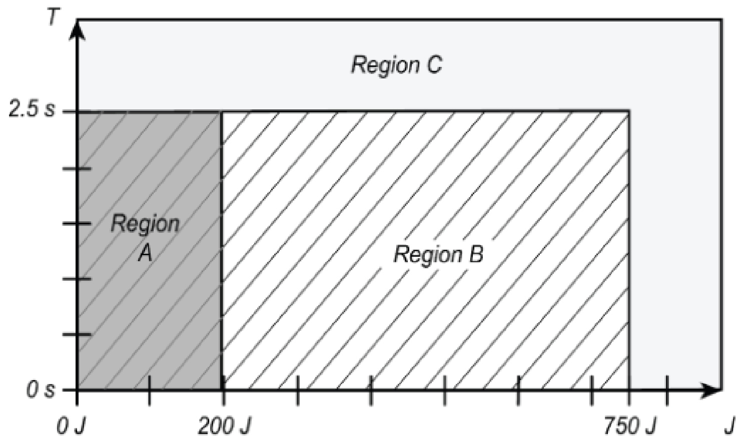

Figure 5: Illustration from UL1699B of the time and energy requirements, also set by IEC 63027, for detecting arc faults, [11]

5 Fronius Arc Guard

The Fronius safety concept focuses on 2 levels:

- The first and fundamental level is risk minimization (passive): the risk of DC arcs should be reduced as far as possible by proper system design, installation, and maintenance. Best practice includes **minimizing the number of connection points**, ensuring that all connections are properly implemented, as well as providing quality assurance through installer training, regular maintenance and inspections. These measures will reduce the number of potential arc faults that arise and require attention.
- The second level is the actual extinction of the arcs (active): once the number of possible arc faults has been reduced to a minimum, the safety of the PV system can be further improved with an AFPE.

To provide this second level of protection, Fronius has developed a state-of-the-art arc detection and interruption technology, the Fronius Arc Guard.

When developing this technology, Fronius was able to draw upon extensive know-how and many years of experience on arc welding from its Perfect Welding division. This resulted in robust technology built on top of the classic FFT-based spectral arc detector, and further developed with advanced techniques for pattern recognition. The Arc Guard also makes use of a trained arc detection algorithm that is regularly improved by Fronius R&D, in order to steadily increase detection accuracy over time.

6 Increased safety without compromises with the Arc Guard

PV systems are already very safe. Statistically more than 99.994% of installed systems will not be affected by fire, so the number of “safe installations” is already extremely high. This means, that any attempt to raise this percentage higher still could result in a relatively small increase (for instance 0.001%). Therefore, **any additional safety measure should be carefully evaluated,** ensuring that the benefit (small) does not incur any side effects, making the use of such a measure questionable.

An example is the use of module-level power electronics. Their shutdown function is supposed to increase safety for firefighters, but the deployment of such electronic boxes under each PV module introduces a high number of DC connectors in the PV array (although they should be minimized in the first place, as a fundamental first-level protection). The risk of electric arcs is actually increased, and so is the risk of fire, as pointed out by the IEC TR 63226, an IEC technical report that provides guidelines for reducing fire risks for PV systems on buildings [3].

On the other hand, the **additional safety** provided by the Arc Guard is achieved by using software and hardware that is **integrated** within the inverter, so no additional external devices or boxes are needed, and **no additional connection points** are introduced in the system. It also means that there is no additional effort during installation.

Moreover, as an AFPE, the Arc Guard is based on the precautionary principle, that is: it detects and **extinguishes arcs before they can lead to a fire**. When the Arc Guard recognizes an “arc state”, the power stages of the inverter interrupt power transmission and stop power feed-in into the grid. In this way the current flow is interrupted, and the arc extinguishes.

As the **Arc Guard further reduces the probability of a fire**, it is also the best protection for emergency responders, because **no fire means no risk for firefighters**.

7 References

[1] Fraunhofer ISE "Recent Facts about Photovoltaics in Germany", Fraunhofer ISE, Division Photovoltaic Modules, Systems and Reliability, Freiburg, 2021.

[2] BRE National Solar Centre, "Fire and Solar PV Systems – Investigations and Evidence", 2017.

[3] IEC TR 63226, "Managing fire risk related to photovoltaic (PV) systems on buildings", 2021.

[4] Shibo Lu, et al., "Study on DC Series Arc Fault in Photovoltaic Systems for Condition Monitoring Purpose", in *Australasian Universities Power Engineering Conference (AUPEC)*, 2017.

[5] TÜV Rheinland Energie und Umwelt GmbH, "Assessment of the fire risk in PV-arrays and development of security concepts for risk minimization", Köln, 2015.

[6] L. E. Norum and F. Schimpf, "Recognition of electric arcing in the DC-wiring of photovoltaic systems", in *INTELEC 2009 - 31st International Telecommunications Energy Conference*, 2009.

[7] Shibo Lu, et al., "A comprehensive review on DC arc faults and their diagnosis methods", *Renewable and Sustainable Energy Reviews,* vol. 89, pp. 88-89, 2018.

[8] M. K. Alam, et al., "A Comprehensive Review of Catastrophic Faults in PV Arrays: Types, Detection, and Mitigation Techniques", *IEEE JOURNAL OF PHOTOVOLTAICS,* vol. 5, no. 3, pp. 982-997, 2015.

[9] G. Artale, et al., "DC series arc faults in PV systems. Detection methods and experimental characterization", in *22nd International Workshop on ADC and DAC Modelling and Testing*, 2020.

[10] NREL, National Renewable Energy Laboratory, "Low Cost Arc Fault Detection and Protection for PV Systems", 2013.

[11] UL 1699B: 2018, "Standard for Photovoltaic (PV) DC Arc-Fault Circuit Protection".

[12] K. Yang, et al., "A Novel Arc Fault Detector for Early Detection of Electrical Fires", *Sensors,* vol. 16, no. 4, p. 500, 2016.