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Safety issues in PV systems: Design choices for a secure fault detection and for preventing fire risk

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ABSTRACT

Photovoltaic systems have played a key role over the last decade in the evolution of the electricity sector. In terms of safety design, it's important to consider that a PV plant constitutes a special system of generation, where the Direct Current (DC) presence results in changes to the technical rules. Moreover, if certain electrical faults occur, the plant is a possible source of fire. Choices regarding the grounding of the generator and its protection devices are fundamental for a design that evaluates fire risk. The subject of the article is the analysis of the relation between electrical phenomena in PV systems and the fire risk related to ensuring appropriate fault detection by the electrical protection system. A description of a grid-connected PV system is followed firstly by a comparison of the design solutions provided by International Standards, and secondly by an analysis of electrical phenomena which may trigger a fire. A study of two existing PV systems, where electrical faults have resulted in fires, is then presented. The study highlights the importance of checking all possible failure modes in a PV system design phase, to assess fire risk in advance. Some guidelines for the mitigation of electrical faults that may result in a fire are finally provided.

Introduction

The energy generated by photovoltaic (PV) systems have played a key role over the last decade in the evolution of the electricity sector, offering a unique opportunity for the growth of mixed production of electricity on a large scale [1–3]. The energy produced by PV systems in Europe, which currently amounts to 4% of peak demand on the continent (with 51 GW installed), could reach a maximum of 25% of European demand in 2030, contributing greatly to the reduction of greenhouse gas emissions and decreasing use of fossil fuels [4,5]. The need for specific Standards to provide clear and practical guidelines for the design of safety in a PV system, and to regulate the connection to the public network became mandatory.

Concerning the design of safety, it's particularly important to take into account that a PV plant constitutes a special system of generation in which the presence of Direct Current (DC) results in changes in the application of general technical rules, and the system itself is a possible source of fire should certain electrical faults occur. Choices regarding the layout

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Abbreviations: AC, Alternative Current; DC, Direct Current; GFPD, Ground-fault Protection Device; IMD, Insulation Monitoring Device; PV, photovoltaic; RCD, Residual Current Detector; RCM, Residual Current Monitor; SPD, Surge Protection Device.

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of the system, the grounding of the negative pole of the DC side and the means of protection are fundamental for the design of a system that accounts for the risk of fire.

The specification for the safe design of a PV system is currently defined by International Standards: NEC 2011 and UL1741 for the countries of North America [6,7]; IEC 60364-7 and IEC 62257-7 for the countries of the European Community [8,9]. To date, the questions relating to the start of a fire in case of electrical failures in PV systems have been solved according to the type of system and through the study of real cases, although some Standards do not refer to the problems, while others have not been updated in relation to the use of the newest protective equipment. The problem of fire in PV systems for electrical faults is therefore still open and worthy of attention.

The subject of this article is the analysis of the relationship between electrical phenomena, that can occur inside of a PV system, and the related means of protection (depending on the system architecture), that can determine the occurrence and development of a fire. For this purpose, in Section "Grid-connected PV systems", a brief description of the elements of a typical grid-connected PV system is followed by a detailed analysis of the design solutions provided by different International Standards and a comparison of the safety performance of these solutions. In Section "PV power plant: fire risk and safety issues" the authors report on electrical phenomena which may trigger a fire in an electrical system, and set these phenomena in the context of a specific case of a PV plant. Section "Two case studies: fire risk from electrical faults in grounded PV plants" includes the analysis of two case studies of existing PV systems, in which there has been an electrical fault resulting in the development of a fire: this analysis highlights the importance of checking all possible failure modes in a PV system in the design phase, in order to assess the risk of fire in advance. Section "Conclusions" summarizes the conclusions and provides some guidelines for the mitigation of the problems associated with specific electrical faults that may result in a fire.

Grid-connected PV systems

PV systems are distinguished in terms of their working conditions in relation to the grid in stand-alone and grid-connected PV systems. The first systems are not the objective of this paper and so they are not here described. The second systems are the objective of the analysis and so a description of their main components and layout is provided.

The grid-connected PV systems are connected to large independent grids (typically public) and can feed power either directly into a residential or commercial building or back into the grid. Its main components in the DC side and the AC side are represented in Figs. 1 and 2. They are: PV generator, consisting of panels connected together in series/parallel configuration to form strings, that can constitute either one array or multiple sub-arrays; inverter, equipped or unequipped with a high or low frequency transformer; possible storage system (typically electrochemical, as batteries); grounding system; devices protecting against over-current in the DC and AC side; Surge Protection Devices (SPD); interface system to the grid. A PV system can include one or more generators, according to the power produced.

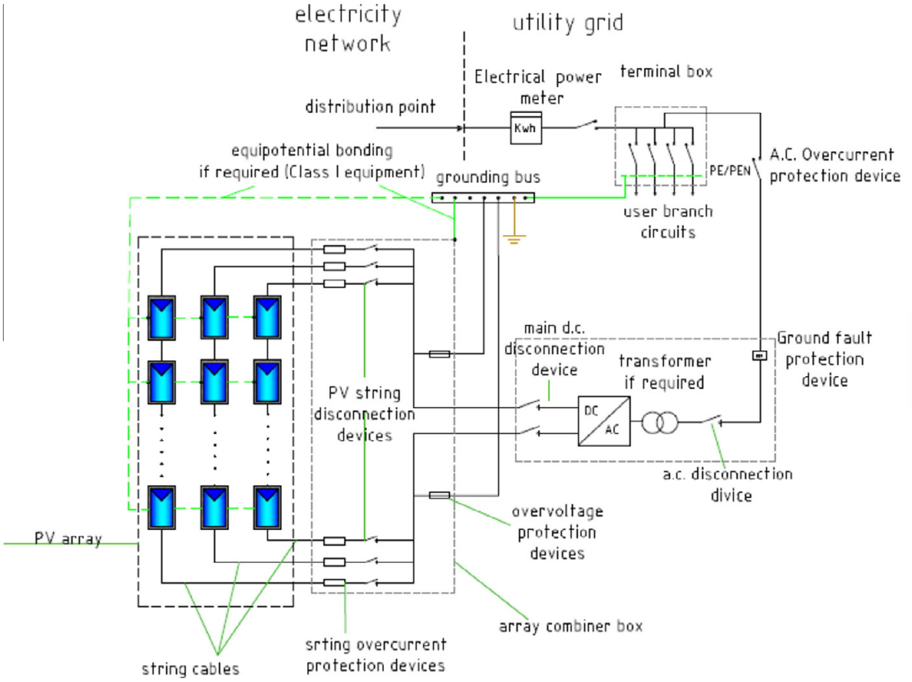

Fig. 1. Typical PV system layout with one array.

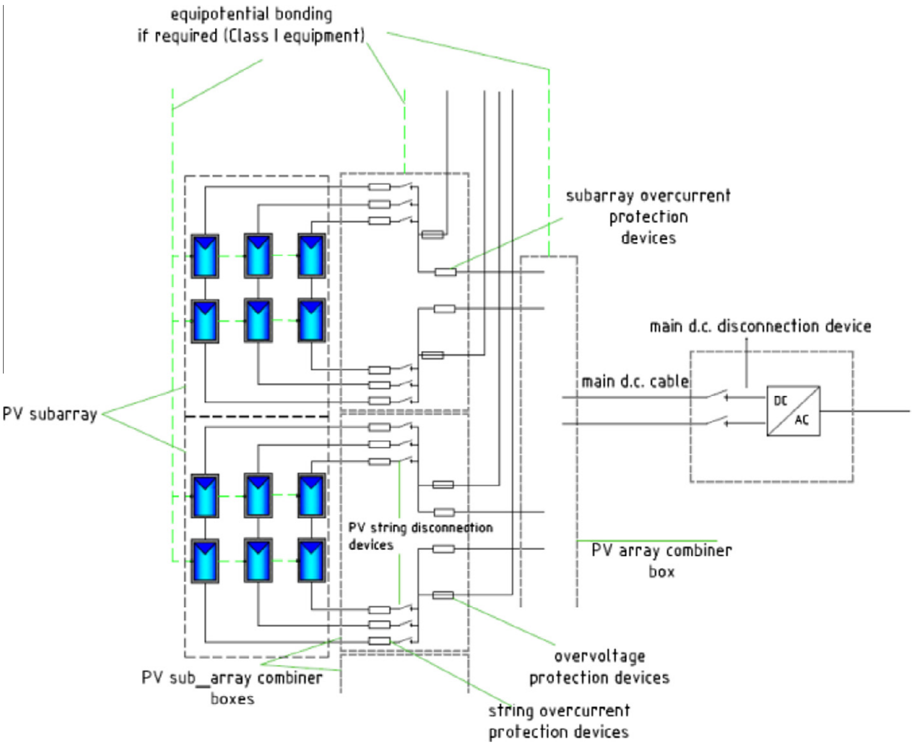

Fig. 2. Typical PV system layout with more sub-arrays.

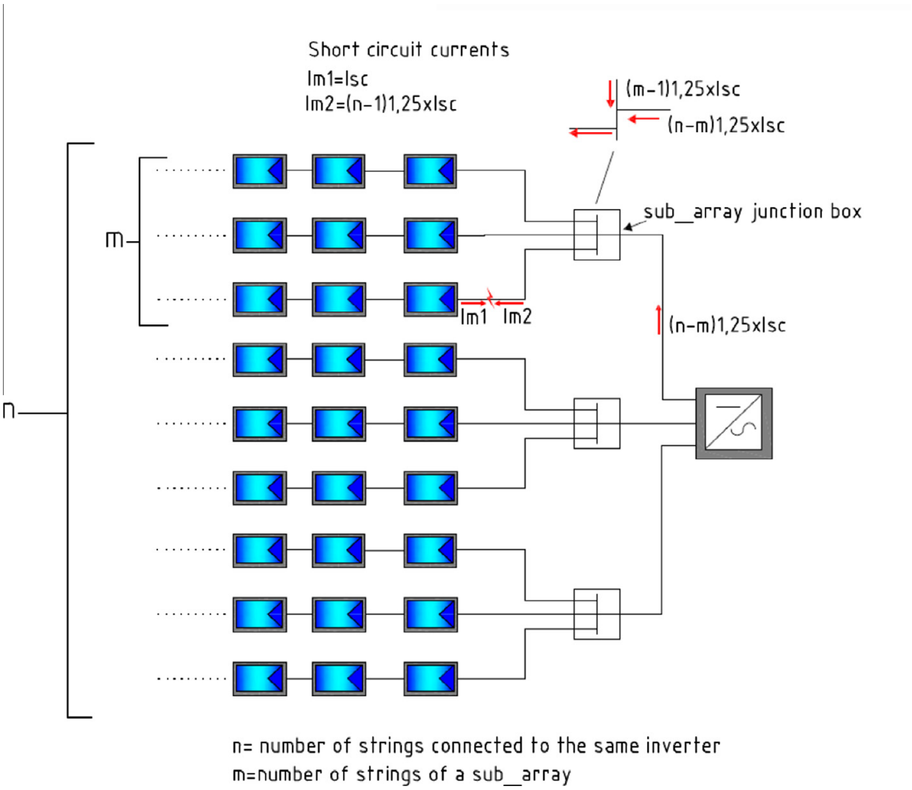

Fig. 3. PV string cable short circuit (single-line representation).

Each generator, which is headed by a single inverter, can be characterized by a single array, as shown in Fig. 3, or from multiple arrays (sub-arrays), as shown in Fig. 4, each of which is composed of a series of strings in parallel connected to the junction box of the PV generator.

If designed in accordance with technical Standards, a PV system cannot be subject to overload; consequently it doesn't need a protection device for this purpose. The cables of the PV system can however, be affected by a short circuit current in the event of: fault between the two poles of the DC system; ground-fault in systems with a grounded point; double ground-fault in isolated systems. The main difference between a normal plant powered by the network, and a PV system resides in the fact that a PV system is a generator. As a result, as shown in Fig. 3, in the presence of a short circuit on a string cable, the fault is fed from one side by the string affected by the failure, and from the other by the current generated by all the other strings in parallel (reverse current). This fault current flows to the path characterized by lower impedance, which in this case coincides with the string affected by the short circuit. The result is that, in the event of a short circuit, a string cable can be subjected to a current equal to the current of the generator, making the protection of strings being needed, unless it is not sized to withstand the reverse current.

The same phenomenon occurs if the fault is localized in a subarray cable, as shown in Fig. 4. Also, in this case, if the cable in question is not sized for the current of the generator, it is necessary to install a protection device in the main DC junction box. Given the small short circuit currents, to protect the system from short circuits, it is common to use fuses or circuit breakers with small rated currents (when necessary). The inverter is located downstream of the main junction box, that contains the protective devices of the PV field. It may be single-phase or three-phase with respect to the power plant. Single-phase systems are common with power up to 10 kW, while with hundreds of kW three-phase systems are generally used. The presence of one or more inverters in a PV system depends on the power plant. Typically, for PV generator power up to 6 kW, modules are divided into one or two strings which feed a single-phase inverter, while for higher powers and three-phase loads it is possible to evaluate whether to install one three-phase inverter, or multiple single-phase inverters. Very frequently the inverter can also be integrated with a transformer, which performs two main functions: to adjust the voltage level of the primary circuit of the system to the network and to provide an inherent protection against the closing of DC current through the network. The inverter is always equipped with a device, for the protection of the PV system from the effects of surges that is called a Surge Protection Device (SPD). PV systems, typically located outside of buildings and often on their

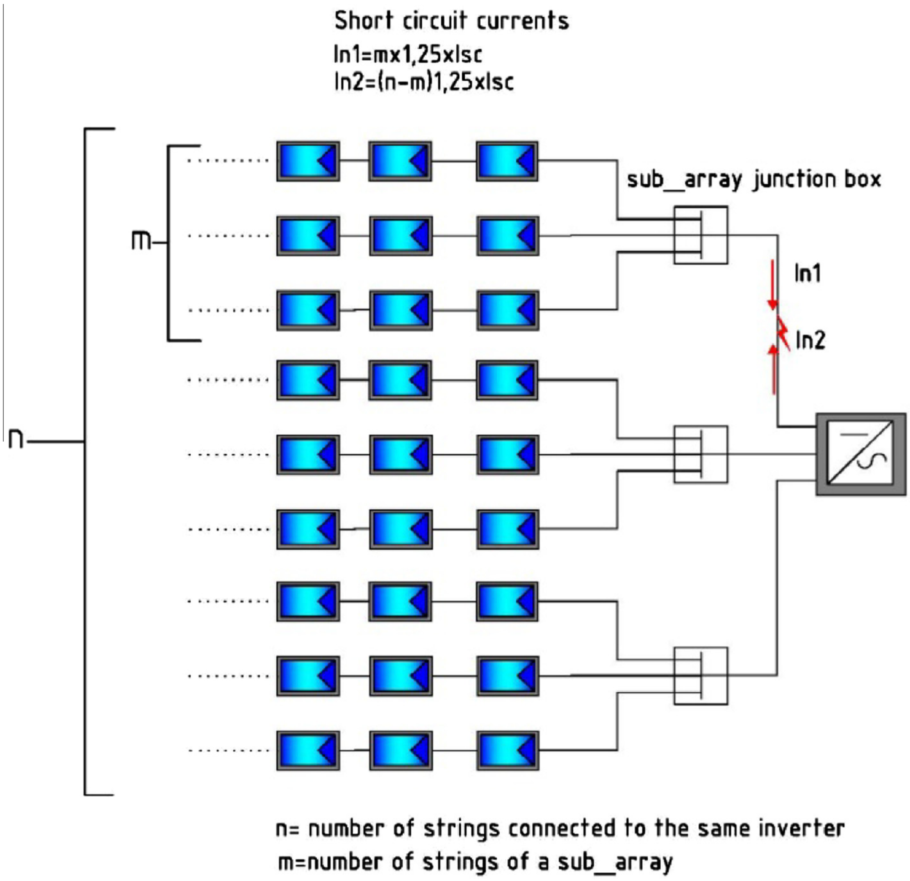

Fig. 4. PV sub-array cable short circuit (single-line representation).

roofs, are exposed to surges caused by lightning, both through direct strikes and indirect strikes. SPD devices are installed to protect the PV system from indirect lightning strikes, which can create surges in electrical circuits mainly through inductive coupling. In particular, the DC wiring that connects the PV modules typically has the form of a closed loop that often causes inductive couplings with the electromagnetic fields generated by lightning. Depending on the exposure of the circuits, it may be necessary to supply the strings with SPDs.

A PV generator, similarly to any electrical system, must be provided with a grounding system coordinated with appropriate safety devices for protection against indirect contact in the case of Class I equipment. The layout of the grounding system varies depending on the type of plant, which can be:

- with the generator negative pole grounded at the inverter; the equipment grounding conductor of DC Class I equipment is connected to the grounded conductor of the generator (commonly used in North America);
- with the generator isolated from the ground: the equipment grounding conductor of the Class I equipment of the DC side is connected to the same grounding terminal used for the AC (mainly used in Europe).

In order to connect a PV system to the grid, a set of devices of protection are provided to perform the appropriate functions to prevent the PV generator feeds the network in case of abnormal values of voltage and frequency. In general, the choice of the components of the interface depends greatly on the layout used (grounded system or isolated system): the phenomena that can occur in the event of a fault in relation to the layout are diversified by imposing a correct management of the fault, such as to coordinate the use of certain protection devices with the related system.

Layout options

A PV system can be designed, in relation to the grounding of the generator and the transformer presence, as: an ungrounded with transformer, an ungrounded without transformer and a grounded PV system.

Ungrounded PV systems with transformer

Fig. 5a and b shows an ungrounded PV system with a transformer, typically used in Europe and defined by [9]. The main feature of its layout resides in the fact that the presence of a ground-fault in the DC side involves no flowing of the current on the network, thanks to the presence of the transformer. This transformer determines the galvanic separation between the generator and the network itself. If all system components are provided with double insulation, as shown in Fig. 5a, the system is intrinsically safe, and does not require the use of any grounding system. The situation is different in the presence of Class I equipment (simple insulation). In this case, a ground-fault determines the flowing of a small ground-fault current on the DC side, due to the leakage capacitance of the PV generator, as shown in Fig. 5b [8]. In order to increase the level of safety and to decrease the likelihood of ground-faults, IEC 62257-7 Standard [9] (and successively the draft version of the AS/NZS5033 Standard [9]) recommends using components in Class II (double insulation) wherever possible.

The occurrence of a ground-fault, both in the presence of Class I and Class II equipment is monitored by an Insulation Monitoring Device (IMD), supplied with the isolated inverter, by most of the manufacturers. The only technical Standards to explicitly recommend the use of an IMD in a PV system are the AS/NZS 5033 and the UL1741, both of which are currently in phases of review. The scientific publications [10,12,13] also stress the importance of using an IMD: this device warns of the occurrence of a first ground-fault, allowing its rapid detection and the automatic disconnection of supply to the network. The IMD device, as shown in Fig. 5a and b, is inserted between one pole of the system and the ground and presents the characteristics contained in the technical standard IEC 61557-8 [14]. The IMD sends a signal to a shutdown system, when the resistance of the plant decays below a specific value (R_{an}), which in turn must be chosen in relation to the minimum value of the insulation resistance of the PV generator ($R_{ISO\ MIN}$), under the worst weather conditions. In order to avoid trouble trips, the value of the rated insulation resistance R_{an} for an IMD device must be chosen according to the following relation [12]:

$$1.5R_{an} \leq R_{ISO\ MIN} \tag{1}$$

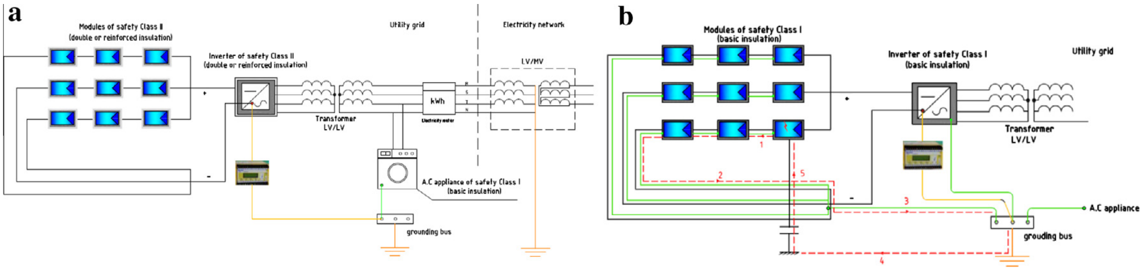

Fig. 5. Ungrounded PV system with transformer and Class II (a) or Class I (b) equipment.

In the standard AS/NZS 5033 [9], the rated insulation resistance of the IMD device must be chosen depending on the system power.

Ungrounded PV systems without transformer

In case of absence of a transformer, the ungrounded PV system is an extension of the network and is grounded via the network itself. As shown in Fig. 8, all Class I equipment must be connected to ground, and the safety of the system depends upon the automatic disconnection of the supply. In case of a DC ground-fault, the current flows through the grounding electrode system and the network. It is worth that, following a ground-fault, the supply must be disconnected in the manner and time prescribed by technical Standards [5,6]. Fig. 6 shows how a ground-fault in the DC side determines the tripping of the residual current device installed downstream of the inverter (sensitive to both AC and DC): this device is recommended for ungrounded PV systems without transformer by international technical Standards IEC 60364-7 [5] and AS/NZS 5033 [9] (Fig. 7).

Grounded PV systems

If the PV system is grounded, all the Class I equipment (apparatus with simple insulation) are connected to the grounded point of the generator. In this case, the PV generator can be connected to ground only in the presence of a transformer, which ensures the galvanic isolation, thus preventing the flow of the DC residual current on the AC side. In these systems a first ground-fault can be likened to a short circuit, characterized by a certain reverse current dependent on the point of failure, the number of strings and the number of sub-arrays. The situation that occurs in the event of a ground-fault on an ungrounded string cable and on an ungrounded sub-array cable is shown respectively in Fig. 9a and b, where the contributions of current produced by all the strings in parallel make their way to the fault, as this is the path of least resistance.

A fuse on the grounded pole performs the function of the protective device against ground-faults, known as Ground-fault Protection Device (GFPD) in American legislation. The National Electrical Code (NEC) explicitly states that this type of protection is only intended to guard the installation from the onset of a fire [15]. In order to avoid nuisance tripping, the rated current of the GFPD device must always be greater than the value of the maximum leakage current to ground. The higher the voltage and the extension of the plant, the greater the leakage currents are under the worst conditions. These currents reclose by means of the grounded pole, affecting the GFPD device. The maximum rated current of the GFPD device, integrated in the inverter to the output of the system, is established by the UL 1741 standard: for a rated DC power of 100–250 kW, a GFPD rated current of 4 A is imposed; for a rated DC power superior to 250 kW a GFPD rated current of 5 A is imposed.

A similar protective device has been introduced in the standard AS/NZS 5033, which specifies that the Ground-fault Protection Device must have a minimum rated current such as to meet the requirements contained in the UL 1741 standard [11]. Fig. 8a and b illustrate in details the different current path in case of ground-fault, on the grounded conductor and on the ungrounded conductor respectively. Red lines show the points of passage of the ground-fault current. In Fig. 10b the ground-fault current has a large value given by the whole short circuit current of the generator, while in Fig. 8a it can be characterized by low values generally insufficient to blow the GFPD device. Although the value of the ground-fault current displayed in Fig. 8a depends on the point and the impedance of the fault, it also depends on both the sections of the string equipment grounding conductor and the string conductor. As shown in Fig. 9, if a first ground-fault on the grounded conductor stays undetected, a second ground-fault on the ungrounded conductor can occur independently from the first fault.

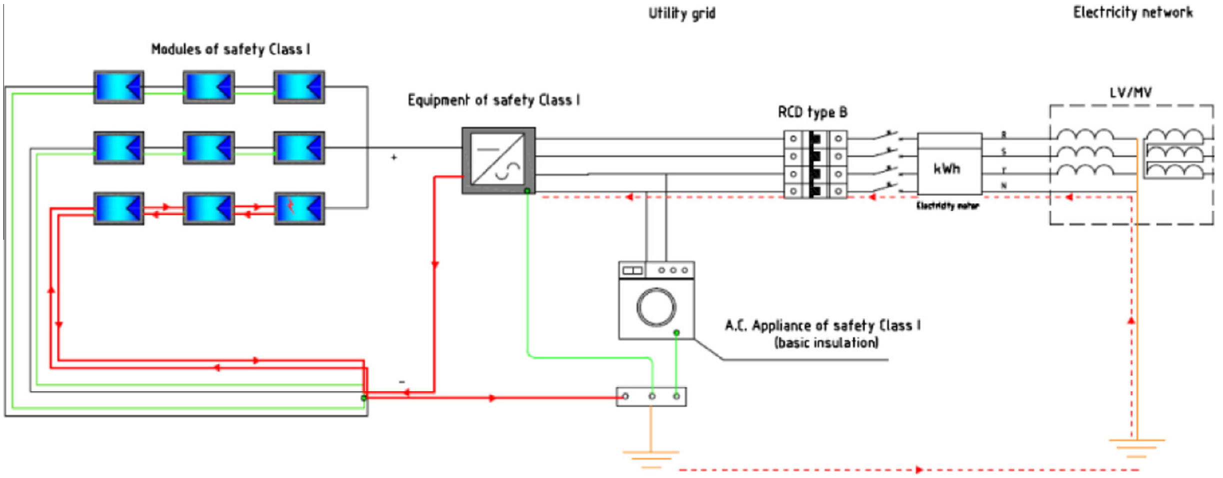

Fig. 6. Use of a RCM in an ungrounded PV system without transformer.

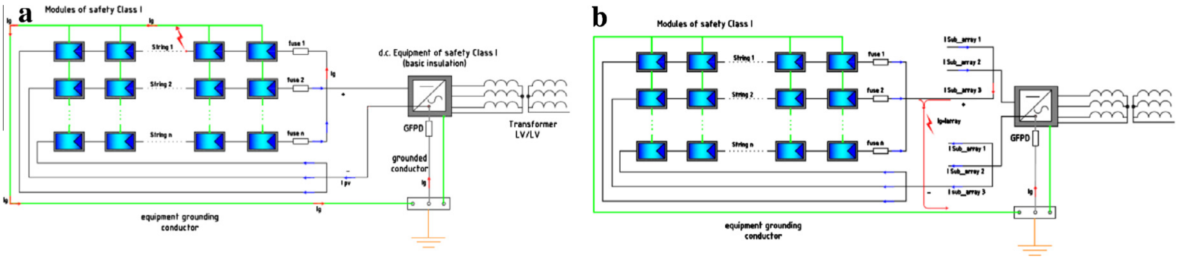

Fig. 7. Layout of a grounded PV system: current path in case of fault on a string (a) or a sub-array (b) conductor.

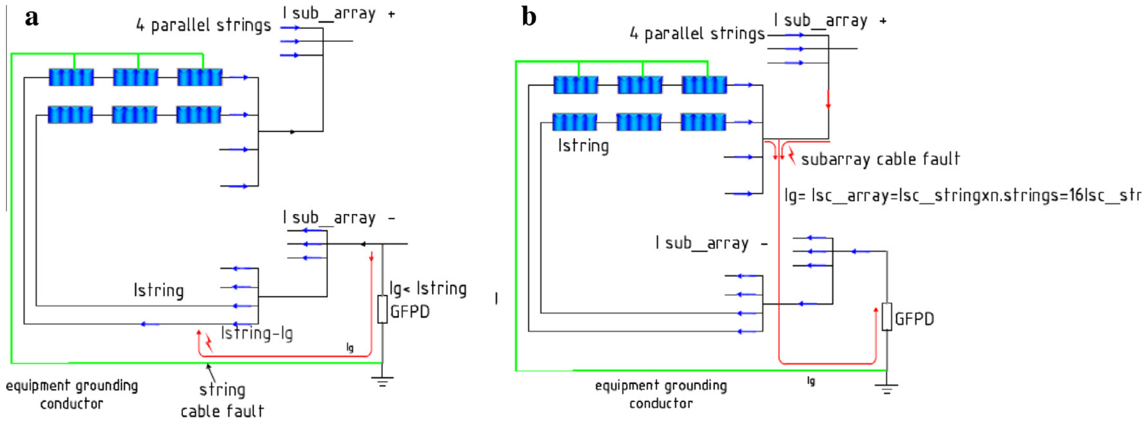

Fig. 8. Current path in a grounded conductor fault for a grounded PV system (a) for a grounded PV system (b).

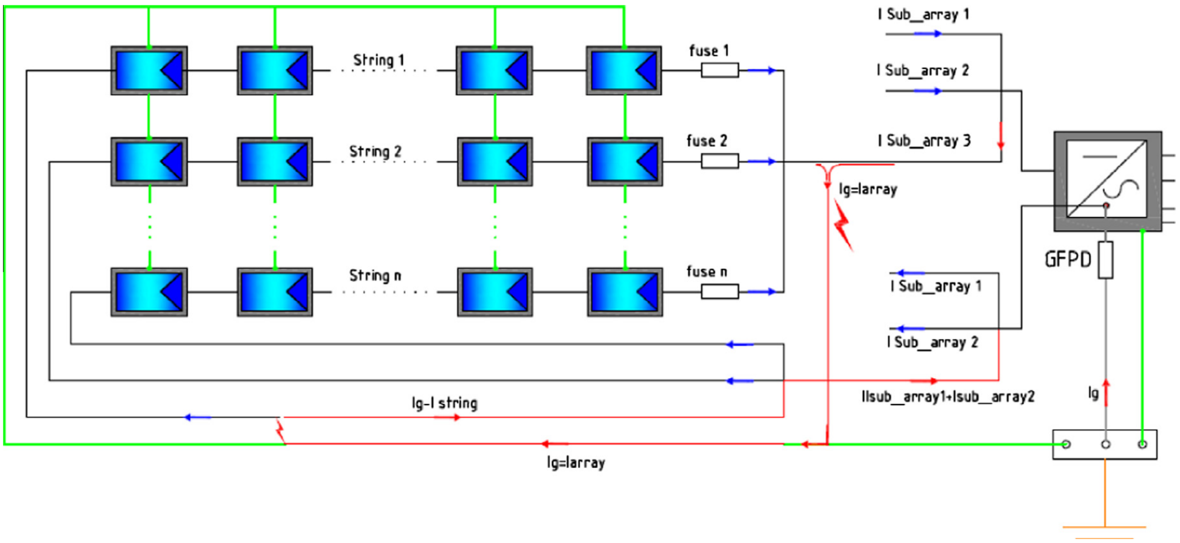

Fig. 9. Double ground-fault in a grounded PV system.

Typical events that may cause ground-faults are either bad assembling of electrical conduits and pipes or loose connections between electrical cables and electrical terminal strips, that may cause either the lowering of the insulation layer or the heating of the insulation layer of the cable. In this case the blowing of the GFPD doesn't avoid the flowing of the fault current which closes through the two points of fault. Fig. 12 illustrates the main differences between the layout of the three systems, in terms of ground-faults and protection devices.

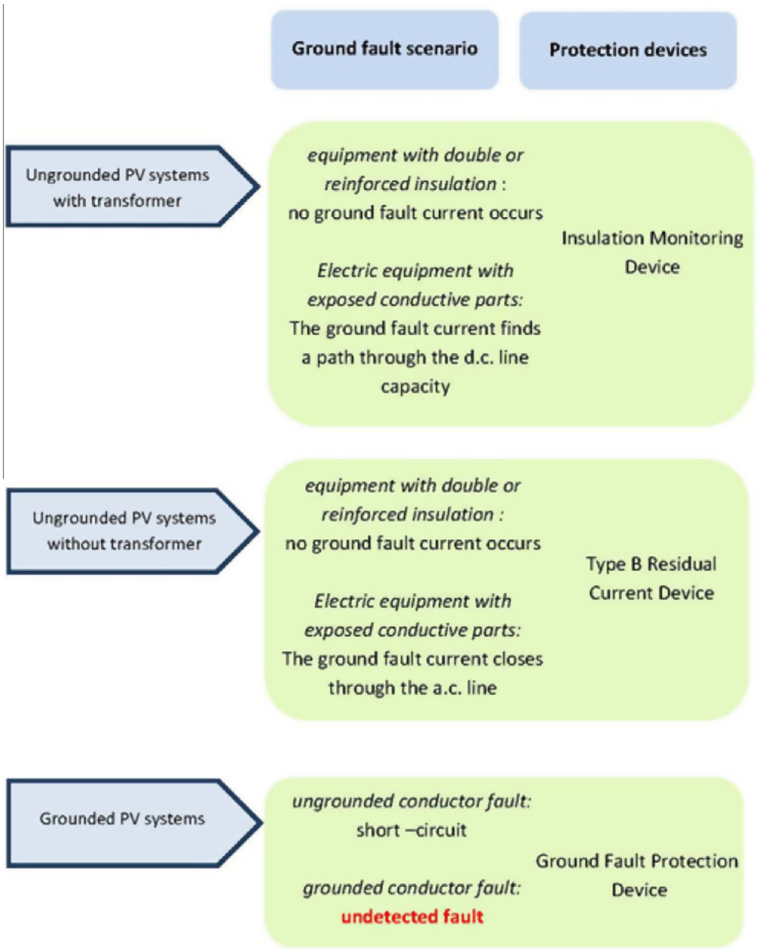

Fig. 10. Main differences between different PV layouts.

PV power plant: Fire risk and safety issues

Recent research studies and scientific discussions have contributed to contemporary analysis of fire risk and safety issues in PV systems, resulting in heightened safety in the PV industry. Wide-ranging concerns have been investigated to support the introduction of certain regulations in standardization groups, enabling fire fighters, building authorities and manufacturers of photovoltaic products to significantly reduce the risk of fire in PV systems [16–32].

In general two substantial causes can trigger a fire in a PV system: the spread of a fire either inside or on the outside of a building; an inner fire resulting from a malfunction within the module or related electrical components (boxes, cables, connectors, DC distribution boxes and inverters). In this paper, fires caused by a malfunction within PV specific electrical components are analyzed. In a PV plant, as well as in all electrical system, a fire can be caused by the presence of short circuits (current with a high value), arcs (current with a low value, generally associated with ground-faults) and poor connections, all three of which may lead to an over-heating of cables and other electrical components [24–32].

The prevention of a fire caused by electrical components in a PV plant is related to the material used to produce modules and electrical components, as well as the plant's design, its installation and its maintenance. Both the proper sizing of the electrical components, in the project stage, and the use of appropriate installation techniques, with high attention to wire management, are fundamental to the reduction of risk. In particular, performing periodic maintenance to identify and resolve any system damage (such as thermal and mechanical stress) is essential, as well as using a data acquisition system to determine if unscheduled maintenance is required.

The development of an electrical fault into a fire in a PV system is closely connected to the layout of the system and the right use of specific protection devices related to each of the system's components (such as string and sub-array cables, inverter, transformer), as explained in Section "Introduction". Depending on the system layout, there can be specific conditions where the Ground-fault Protection Device is not able to detect the ground-fault current, even if chosen according to technical Standards. This event specifically occurs when the ground-fault current has a value lower than the rated value

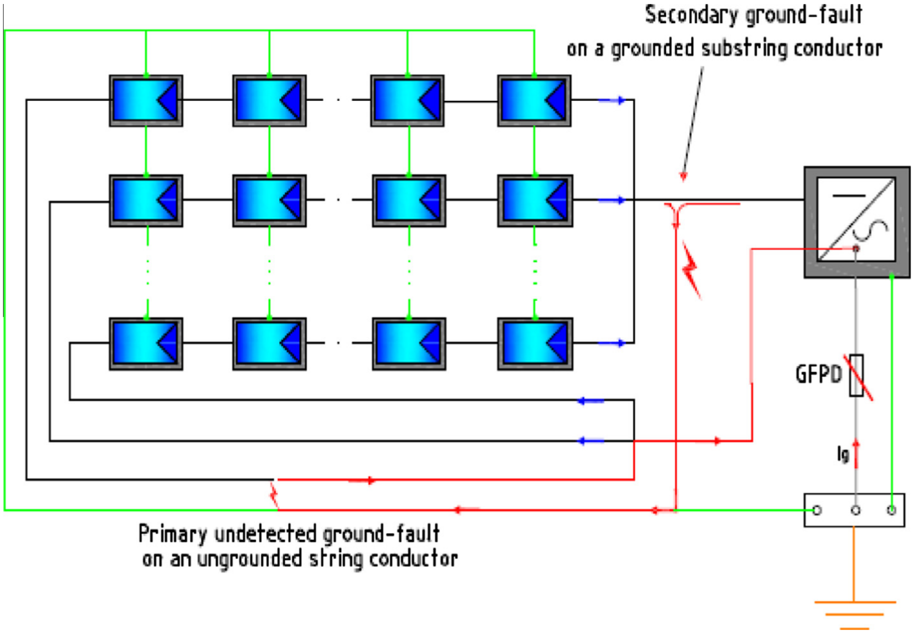

Fig. 11. Possible consequences of the phenomenon of the blind spot.

established by the Standards for the Ground-fault Protection Device (lower limit of detection). In this case the device is defined as having a blind spot.

Recent studies have highlighted that the blind spot phenomenon is more common in grounded PV systems than in ungrounded ones. Depending on the transformer presence in the ungrounded systems, it is common to protect against ground-faults by installing: an Insulation Monitoring Device (IMD) that detects ground-fault currents and monitors the occurrence of any insulation faults, or a Residual Current Detector (RCD). In the case of the grounded systems, the usual protection device suggested by all the Standards is a Ground-fault Protection Device (GFPD) located on the grounded conductor. This device is only able to detect ground-faults on the ungrounded conductor. So in the case of a primary ground-fault on the grounded conductor, the fault stays undetected indefinitely until a secondary fault takes place on one of the ungrounded conductors. As shown in Fig. 11, in the event of this second fault, a short circuit is set up and the GFPD is no longer able to interrupt the fault current, as better explained in the following Section referring to a real case: depending on the second fault point (string, array or sub-array), the short circuit current, occurring after a second ground-fault, may exceed the string conductors ampacity, with the result of a fire.

In the presence of metallic raceways (connected to the grounding system through the equipment grounding conductor), the formation of an electric arc between the faulted conductor and the metallic raceways is possible, should the fault consist of damage to the ungrounded conductor insulation.

In the next Section, two cases of fires within PV systems, located in the USA, are analyzed in order to examine the occurrence of blind spots in grounded PV systems:

(1) The first case (Case A: Bakersfield Fire, California) refers to a fire derived from a primary undetected ground-fault on a string grounded conductor, and a secondary ground-fault on a sub-array ungrounded conductor.
(2) The second case (Case B: Mount Holly Fire, North Carolina) refers to a fire derived from two ground-faults that occurred respectively on a sub-array grounded conductor (primary fault) and a sub-array ungrounded conductor (secondary fault).

Both cases guided the American PV industry to a major awareness of larger safety concerns derived from the practice of grounding the PV array.

Two case studies: Fire risk from electrical faults in grounded PV plants

Two real case studies have been analyzed, with the objectives: to improve an understanding of the complex nature of faults that can trigger a fire in PV systems; to explore the safety implications of suspected inadequate ground-fault-protection. The 2009 Bakersfield fire in California and the 2011 Mount Holly Fire in North Carolina are the only two publicized fires from a multitude of accidents in U.S. PV plants, where most of the plants are grounded, as suggested by the American NEC

Standards. With reference to the official reports, that provided basic insights into the cause of fire, attention is drawn to the key factors that contributed to the fires.

Case study A: Bakersfield Fire, California

On April 2009 in Bakersfield (California, USA), a PV plant caught fire on the roof of a big box store. The system consists of: 7 sub-arrays, each composed of 22 parallel strings, with a maximum current of 159 A per sub-array; a 5 A fuse, installed on the grounded conductor, used as GFPD; 5 A fuses installed on the string ungrounded conductors to provide short circuit protection; 300 A fuses installed on the sub-array ungrounded conductors to provide short circuit protection; string conductors and string equipment grounding conductors with a section of 10 American Wire Gauge (AWG), that corresponds to a European section of about 6 mm^2, and with an ampacity of 40 A; sub-array conductors and sub-array equipment grounding conductor with a section of 750 AWG, which corresponds to a European section of 380 mm^2, and with an ampacity of 535 A[5].

Both string conductors and equipment grounding conductors were placed in metallic raceways, while sub-array conductors and related equipment grounding conductors were placed in metallic pipes. All the metallic raceways and all the pipes were connected to the grounding system. Official reports on the fire event [19,20] write that two electric arcs occurred in two different points of the system: the first arc took place along one of the metallic raceways connecting the strings with the CB7 junction box, as shown in Fig. 12; the second one took place on a metallic pipe joint, connecting the CB7 junction box with the related inverter, as shown in Fig. 13.

The hypothesis is that both the arcs, derived respectively from the damage of a string cable and a sub-array cable, were originally caused by badly assembled conduits. The movement of the ducts coupling under thermal expansion damaged the cables. The drop of the cables insulation voltage at the damaged point (with a system voltage of 500 V) determined discharges between the conductors, and between the conductors and the metallic conduits.

It appears that the root cause of the Bakersfield fire can be found in a first undetected ground-fault on a string grounded conductor. In this case, the ground-fault current splits between the ungrounded conductor and the equipment grounding conductor. If the string equipment grounding conductor section is equal to the string conductor section, the fault current has a maximum value of half the string's current (with a zero fault resistance in the worst conditions). So if the string's current has a maximum value of 8 A, the fault current is between 3 and 4 A, too low to blow a 5 A fuse. In this undetected condition, a ground-fault on the string grounded conductor may exist indefinitely, establishing a new "normal" condition that makes the GFPD unable to clear a second ground-fault.

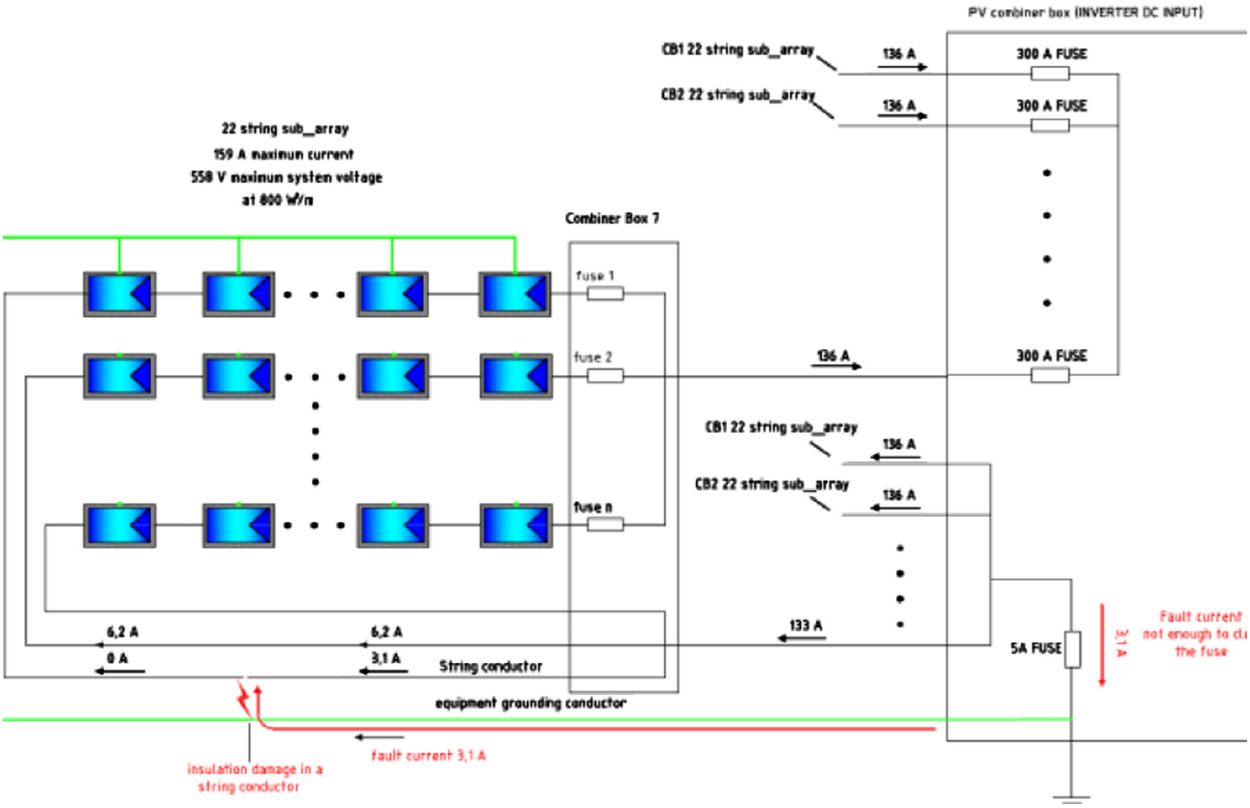

Fig. 12. First ground-fault of the Bakersfield fire.

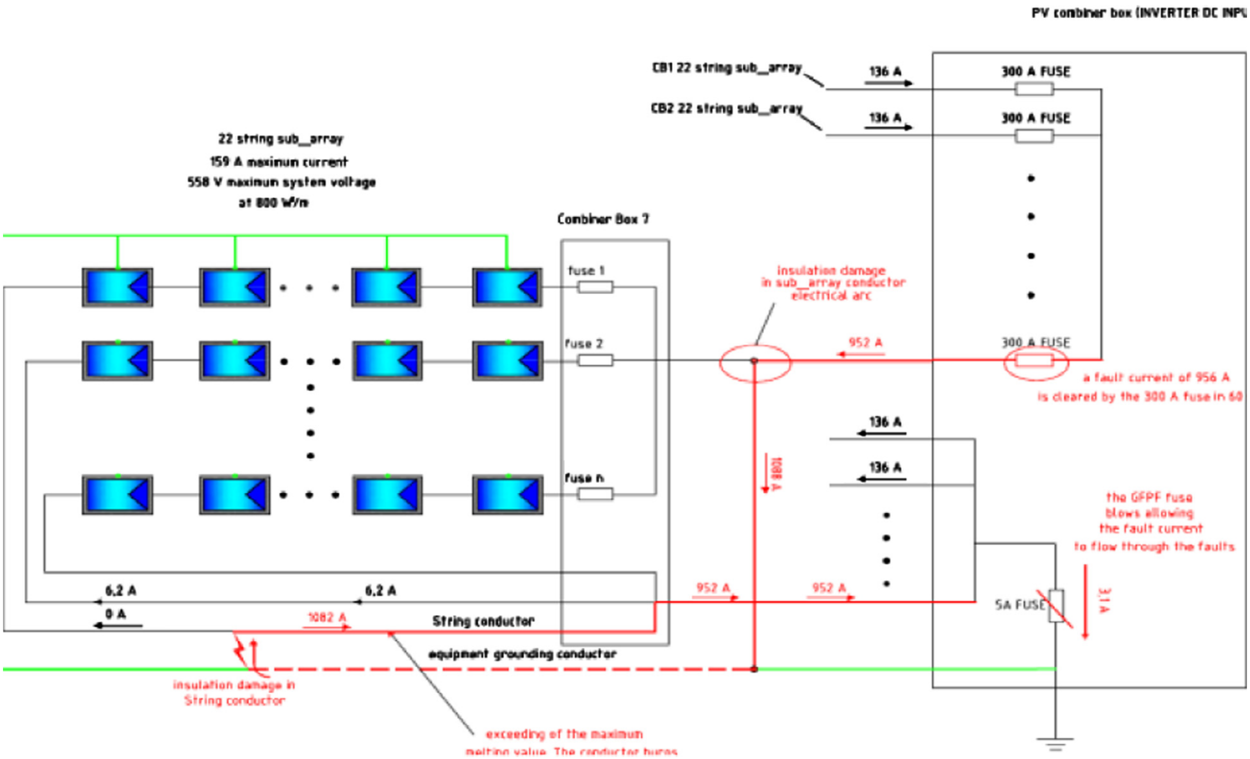

Fig. 13. Second ground-fault in the Bakersfield fire.

In the case of a second ground-fault on one of the sub-array ungrounded conductors, the current produced by all the other sub-arrays flows towards the two faults. This situation induces two electric arcs in correspondence with the two fault points, and a current of about 1000 A which flows through the metallic raceways and pipes, the equipment grounding conductor and the string conductor. The GFPD blows without interrupting the fault current, as shown in Fig. 13. So a current of about 1000 A flows through both a string grounded conductor and an equipment grounding conductor of 10 AWG without blowing the protection device. This condition determines the burning of the wire's insulation.

Because NEC installation requirements do not allow overcurrent protection devices in the grounded conductors of grounded PV arrays, full array current flows unconstrained through the ground-fault in the string-level wires of the system. Fig. 14 demonstrates how the blowing of the 300 A fuse, with a current of 950 A, happens in about 60 s. This time is not sufficient to avoid damage to the insulation of the string conductor of 10 AWG. The heat developed for Joule effect by the fault current burned the insulation layer and appeared to start a fire that spread all along the raceways, determining multiple faults.

In Fig. 15 the specific energy let-through curve of a 300 A fuse and the thermal withstand capacity of a 10 AGW cable isolated with EPR are compared: for tripping times higher than 1″, and a current of about 1000 A, the specific energy let through by a 300 A fuse (20^7 A^2/s) is higher than the thermal withstand capacity of a 10 AWG conductor (10^6 A^2/s). This condition is a cause of fire.

Case B: Mount Holly Fire, North Carolina

The second well-known fire in the USA involving a PV system happened in Mount Holly, North Carolina, in April 2011. The DC system architecture referred to in Case A, is used again, in order to analyze the causes of this fire. The protection devices and the components are the same (Fig. 16).

The official report on the fire event [21] in this case revealed that the fire appeared to have been caused by two electric arcs, occurring respectively in a grounded sub-array cable and an ungrounded sub-array cable. Fig. 17 shows the current path in the first ground-fault, caused by damage to the insulation of the grounded sub-array conductor: the ground-fault in the grounded sub-array conductor causes the current to split and follow two parallel paths from the inverter to the fault point. Even if the sub-array conductor and the equipment grounding conductor have the same section, the fault current might still possess insufficient values to blow the GFPD, depending on the value of the fault resistance.

As in Case A, the first fault on the grounded sub-array conductor remains undetected indefinitely, until a second fault occurred. In the event of a second ground-fault on the sub-array ungrounded conductor, the result is a short circuit unable

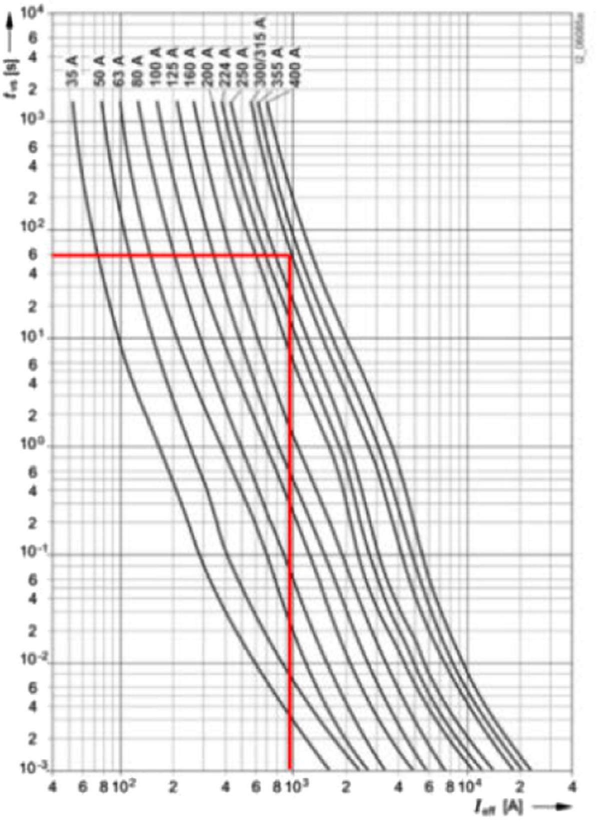

Fig. 14. 300 A fuse time–current characteristic diagram.

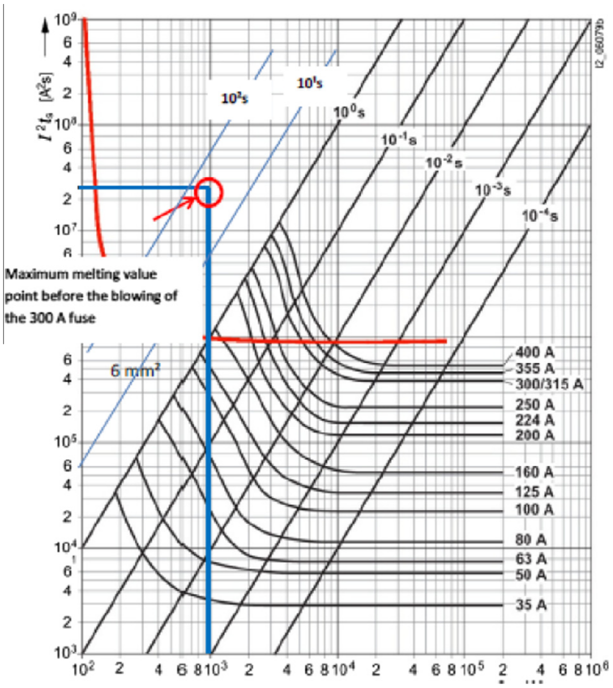
Maximum melting value point before the blowing of the 300 A fuse

Fig. 15. 300 A fuse and 6 mm^2 wire let-through curves.

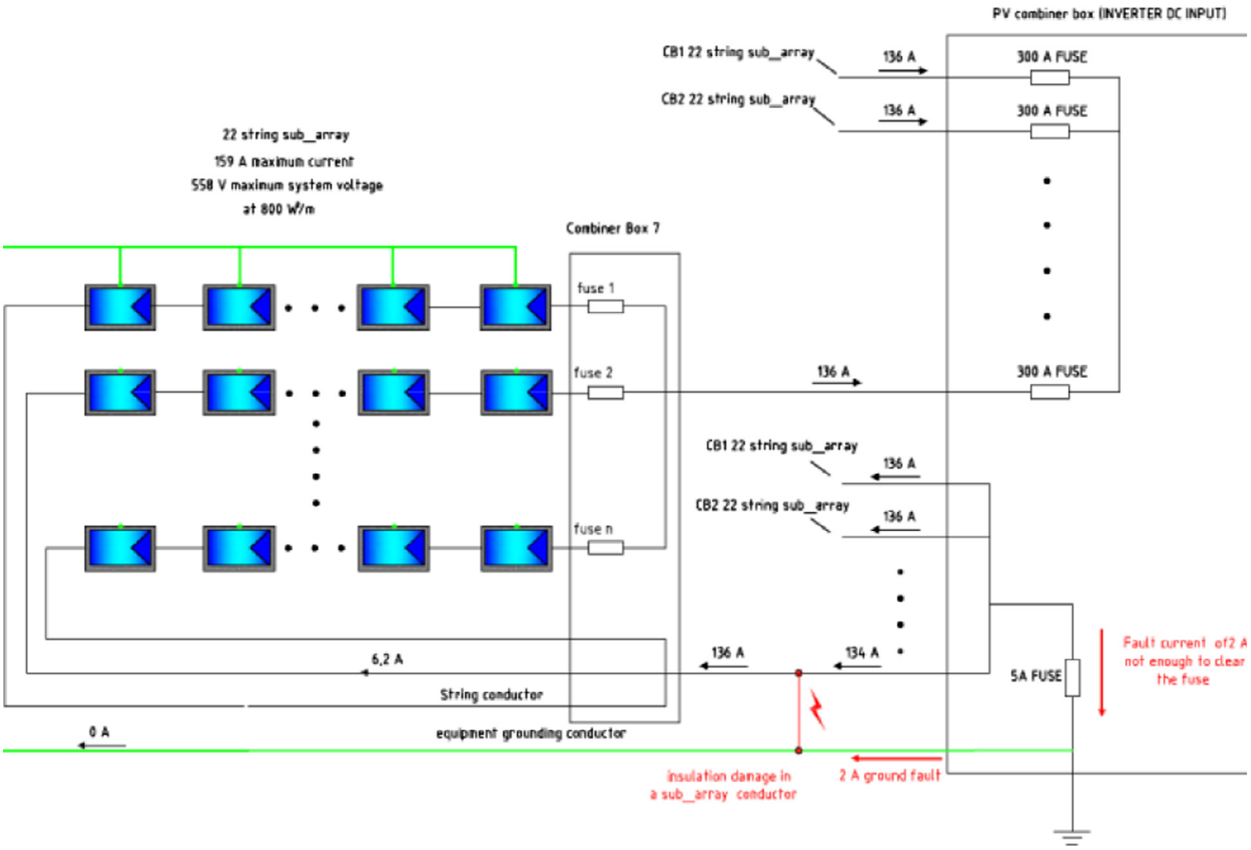

Fig. 16. First ground-fault in the Mount Holly Fire.

to be cleared by the GFPD, as shown in Fig. 17. With the damaged sub-array conductors able to carry the fault current, the fire started solely from the electric arcs that originated in the fault points (between the damaged conductors and the metallic conduits).

By examining a typical PV solar wire used in the USA, it was possible to demonstrate that the root cause of the fire in Case B appeared to have been only the result of the electric arcs: this cable, which fits the installation in a metallic tube, is chosen with an ampacity greater than the fuse rated current, and with a value greater than or equal to 1.56 of the a sub-array short circuit current ($I_{\mathrm{sc\_subarray}}$). Considering a sub-array short circuit current of 162 A, the ampacity value found is reduced due to the temperature coefficient in the NEC standard. The reduction of the ampacity with ambient temperatures greater than 60 °C determines the selection of an AWG-750 wire, corresponding to a European section of 380 mm^2. An alternative can be to install two AWG-290 conductors in parallel, each supplying 50% of the operating sub-array current. Comparing the let-through curve of a 300 A fuse (in correspondence to the PV array short circuit current of about 1000 A) with a 120 mm^2 cable thermal withstand capacity, it is possible to deduce that both a 380 mm^2 section and a 127 mm^2 section are widely protected against the insulation deterioration, as a result of the temperature developed by the Joule effect, considering the value of the current flowing respectively in the two sections (Fig. 18).

Discussion: Fire mitigation strategies and equipment recommendations to prevent blind spot in grounded PV systems

In both of the real case studies, our analysis points out that the fire may have been caused by a blind spot in the 4–5 A fuse used as ground-fault protection, as stipulated by the UL1741 standard.

The use of 4–5 A fuses to protect systems from ground-faults is justified by the high value of the leakage current. Fuses with a high value of rating currents are in fact able to avoid trouble tripping, but are inadequate to interrupt the small fault currents derived from a first fault on the grounded conductor. The value of this fault current depends upon the fault point, the section of the conductors and the fault resistance.

At present, the most reliable solution to prevent blind spots in grounded PV systems is to install multiple small inverters and combine two devices: an IMD device to monitor the insulation resistance of the system [21]; a RCM device sensitive to DC [10,21,22]. Installing multiple small inverters means splitting the total number of PV arrays among more inverters of smaller nominal power. This involves in a smaller leakage capacitive current in the GFPD of each inverter, and so in a smaller size of the device and a better sensitivity resulting in a better detection of ground faults.

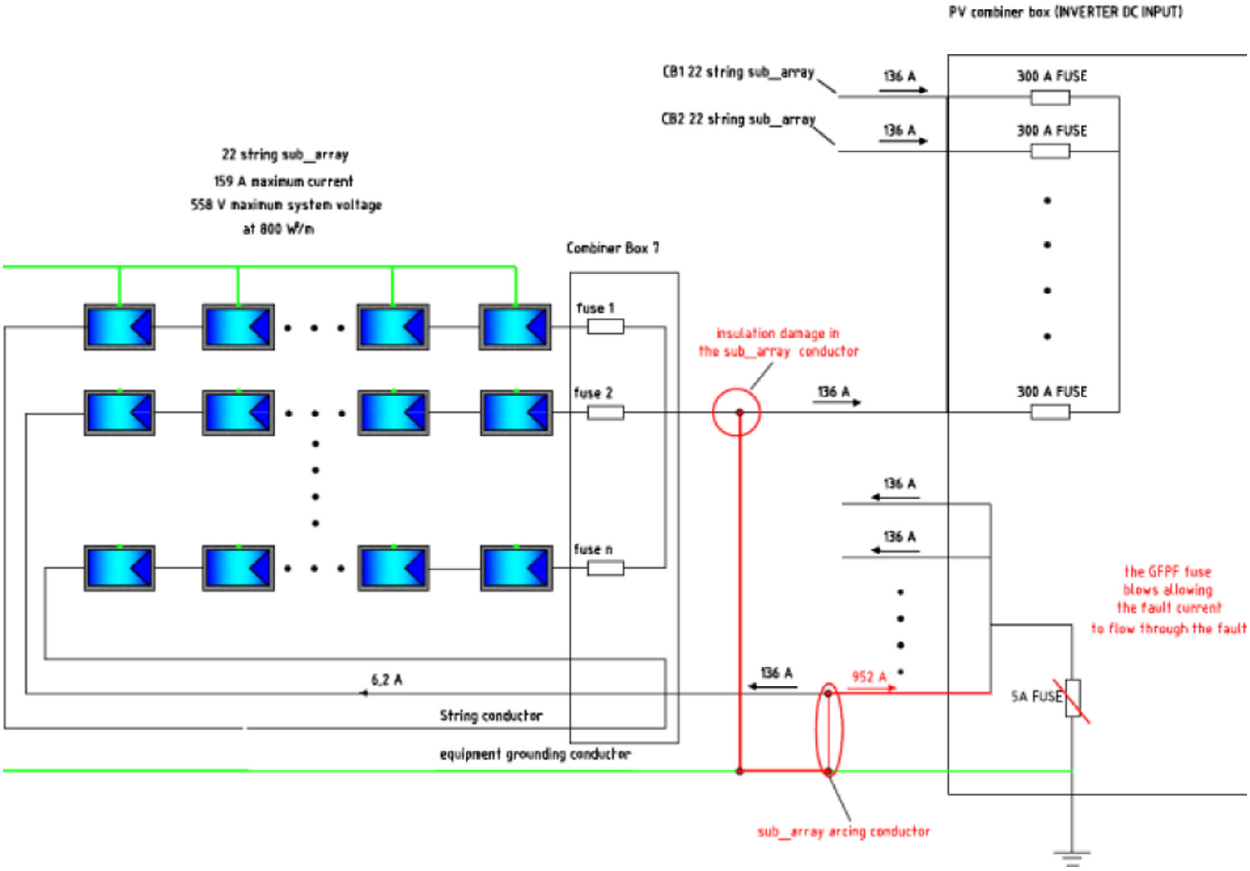

Fig. 17. Second ground-fault in the Mount Holly Fire.

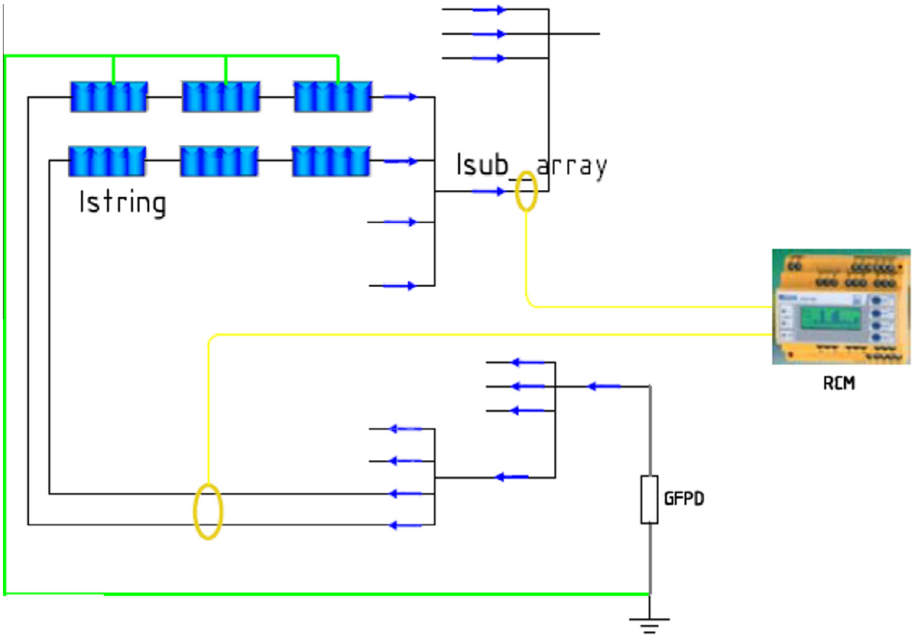

Fig. 18. Positioning of the RCM device in a PV array.

On the other hand, combining an IMD device to monitor the insulation resistance of the system and a RCM device sensitive to DC is the safest way to prevent fire risks caused by ground faults, because a ground fault is originated by a damage in the insulation between active electrical components. Installing an IMD device allows the measurement of the resistance between a point and the ground, and then to detect a damage in the insulation of the system. The RCM can instead detect by electronic components the DC fault, performing the measurement of the direct differential current between more conductors that passes through the device, or the direct measurement of a DC current flowing through one of the conductors. So, although the Standards still do not clearly require the use of a RCM to protect grounded PV arrays, it is currently the only device able to detect both DC leakage fault current and DC ground-fault current.

The key characteristic of an RMC, defined in the IEC 62020 [22], is to have a high sensitivity to small values of DC currents. In order to detect faults, it is installed either on the grounded conductor (within the inverter) or directly on the carrying conductors, with different degrees of sensitivity depending on the point of installation. When choosing the RCM rated residual operating current ($I_{\Delta n}$), the maximum leakage current ($I_{\mathrm{LEAK\ MAX}}$) under the worse meteorological conditions must be taken into account. To prevent nuisance tripping, considering that the trip range should be between 0.5 and 2 $I_{\Delta n}$, the following relation must be verified [7]:

$$0.5 I_{\Delta n} \geq I_{\mathrm{LEAK\ MAX}} \tag{2}$$

Usually to provide the protection against direct and indirect contact, the rated residual operating current $I_{\Delta n}$ is chosen with a value of 135 mA according to the IEC/TS 60479 [32].

Conclusions

A PV plant is a special generation system in which the presence of DC results in changes to the application of general technical rules. Moreover, if certain electrical faults occur, the system itself can become a possible source of fire. The layout of the system, the grounding of the negative pole of the DC side and the means of protection are all vital concerns affecting the design of a system that accounts for the risk of fire.

In this paper, the design solutions provided by different International Standards have been studied and their safety performances compared. The effect of electrical faults in PV systems is significantly governed by these standards and an analysis of the relation between the faults and the related means of protection has been presented.

The focus has then on two case studies of existing grounded PV systems in the USA, in which electrical faults have resulted in the development of fires. In both case studies, the analysis suggests that the fire was caused by a blind spot in the protection device used as ground-fault protection. This evidence emphasizes the importance of checking all possible failure modes in a PV system in its design phase, in order to prevent fire due to blind spots.

The most reliable solution for the avoidance of blind spots is to install multiple small inverters and to combine two devices: an IMD device to monitor the insulation resistance of the system, and a RCM device sensitive to DC Although the Standards still do not clearly require the use of a RCM to protect grounded PV arrays, it is currently the only device able to detect small DC ground-fault currents.

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