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Stray Current DC Corrosion Blind Spots Inherent to Large PV Systems Fault Detection Mechanisms: Elaboration of a Novel Concept

A. Demetriou, D. Buxton and C. A. Charalambous, *Member, IEEE.*

***Abstract* — This article elaborates on a new issue that should progressively receive attention by Photovoltaic (PV) installation industry and utility management entities. It specifically introduces stray current corrosion blind spots that are inherent to PV systems' grounding and associated DC ground fault detection mechanisms. These blind spots arise as the existing thresholds for DC leakage currents have been based on other issues such as fire or personnel safety. Leakage current may cause accelerated corrosion on PV supporting metallic structures as well as on third party metallic utilities that may be present in the vicinity of PV installations. The impact of DC stray current corrosion is recognized by the stakeholders across the world in the DC traction community and codes and standards have been developed to provide designers and utility companies with a corrosion management strategy that defines a level of corrosion risk which is acceptable across infrastructures. This article outlines the theoretical background that will assist the understanding of stray current corrosion by PV plant developers, designers and owners and raise awareness with the utility Distribution Network Owners.**

***Index Terms* — Stray Current, DC corrosion, Photovoltaic Systems, Fault Detection, Grounding**

I. Introduction

LEAKAGE currents in Photovoltaic (PV) systems come as a result of a fault or from the systematic and inevitable flow of direct current (DC) through non-ideal materials of the cables, PV modules and other array components. The Solar America Board for Codes and Standards (Solar ABCs) has issued a white-paper - "*Ground-Fault Protection Blind Spot*" [1], to raise the awareness of PV System Owners to appraise both the benefits of system retrofits and the risks associated with not implementing any strategies for the early detection of PV ground faults and leakage currents. The safety issue associated with the non-detection of PV ground faults has been highlighted after the two known PV system fires in Bakersfield, California (2009) and in Mount Holly, North Carolina (2011). The official reports, based on evidence collected from these two fire-events, are given in [1]-[2]. The conclusion of the two case studies [2] was that some ground fault protection schemes may not detect certain common ground faults in PV systems. These undetected faults - as termed by Solar ABCs - fall within detection "blind spots", intrinsic in the design and installation of PV systems (mainly grounded).

Nonetheless, one challenge for PV systems' inverters is that they should reliably disconnect under real fault conditions, without experiencing "nuisance" trips from regular and inevitable leakage currents. The arising question is however, how well defined or understood is the threshold for regular and inevitable leakage currents? Should it be defined based on an acceptable energy loss performance of PV Systems? Or alternatively, should it be dependent on safety issues related to fire ignition or humans' protection against electric shock [3]-[4]? To what extent is this threshold affected by weather conditions [5]?

This article will attempt to pose another question relating to the DC leakage detection practices associated with PV systems. Should corrosion damage be considered? We will attempt to demonstrate that, under certain conditions, the DC leakage currents, if left unattended, or not detected at all, may cause accelerated stray current corrosion on metallic structures (e.g. racks, joints, conduits, enclosures-boxes) or on metallic underground infrastructure (e.g. metallic pipelines) buried in the vicinity of large, utility-scale PV systems.

For those not familiar with the term, stray current corrosion it refers to corrosion damage to metallic infrastructure resulting from DC flow other than in the intended circuit. In this paper the stray current corrosion damaging mechanisms are conceptually correlated to those investigations that have uncovered evidence for persistent but undetected DC ground faults / leakage currents [1], [2], [6] in PV systems both grounded and floating (ungrounded) [7].

II. PV Systems DC Grounding Methods

Photovoltaic (PV) systems are no different from other electrical power systems and therefore they should be grounded to eliminate shock, lightning surges and possible fire hazards [8]. The grounding system of a utility-scale PV plant embraces the Medium Voltage (MV) substation's grounding system, the inverters' housings (AC) grounding provisions as well as lightning protection grounding electrodes. PV parks' fences are appropriately grounded as well, depending on the specific risks and hazards identified [9].

The DC side of PV systems (DC PV arrays) can be also grounded and based on their type of grounding, the systems are classified as grounded or floating (ungrounded) [7],[10],

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(Fig. 1). A grounded PV system has either the positive or negative DC-carrying conductor connected to ground thus a distinct reference point to earth can be defined. In such a system the inverter may electrically isolate the AC and DC side should it embrace a transformer benefiting from galvanic isolation. The grounded configuration is commonly used in U.S commercial PV parks and should comply with the national standards described in [11], [12].

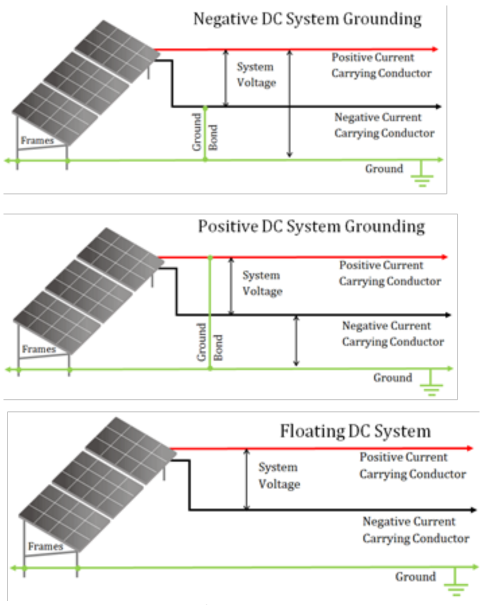

Fig. 1. Types of PV Systems Grounding

A floating or ungrounded PV system has neither the positive nor negative DC current-carrying conductor connected to ground. The inverter in floating PV systems may have a transformer providing galvanic isolation between DC and AC side or alternatively it may be transformerless (non-isolated). The floating configuration is most frequently used in Europe. A common misunderstanding about floating PV systems is that they lack all connections to ground, including the bonding to ground of exposed metal (e.g. metal frames of the PV modules, supporting infrastructure, combiner boxes) that could become energized in a fault situation or under normal operation due to coupling mechanisms [3],[13]. This perception (i.e. lack all connections to ground) is not true however. Both grounded and floating PV systems have their metal equipment grounded to earth (Fig.1) to maintain the electrical potential of any exposed metal parts at zero volts. That is to facilitate the operation of protection devices to assist in keeping systems and people safe.

III. Leakage Currents and Ground Fault Detection Mechanisms

A. Source of DC Leakage Currents in PV Systems

PV generators are classified as DC power systems. All conductors and elements of direct current systems should be insulated from earth. The total ground leakage current, is formed by the contribution of all system components (e.g. PV modules, DC cables, Inverters) when taken together. For a certain voltage level, this leakage current is dependent on the effective insulation resistance that is known as R_{ISO} (see Fig.2). The effective insulation resistance can be measured before connecting the PV system to the grid [7] and it provides an indication of the magnitude of the anticipated leakage currents to ground. It is worth noting that the DC leakage currents can be alternatively sensed as the difference between the positive PV and negative PV currents coming from the PV array to the inverter.

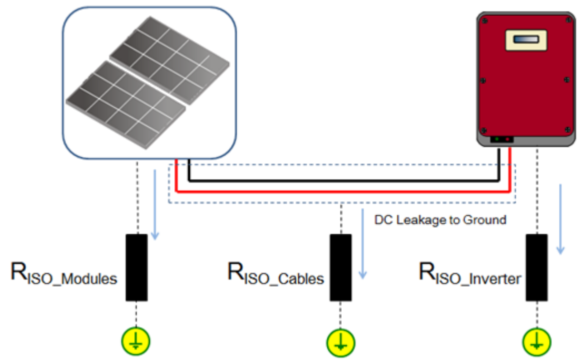

Fig. 2. Effective Insulation Resistance (R_{ISO}) of a PV System Decomposed in Constituent Elements

B. Magnitude of DC Leakage Currents in PV Systems

The PV system is a current-limited source and the level of PV current and associated leakage current are thus dependent on external factors such as solar irradiance and other environmental conditions which include ambient temperature, soil resistivity etc. [3], [5].

For the proper operation of the inverter the PV modules are connected in series strings to usually achieve a voltage level between 600Vdc and 1000Vdc. The minimum insulation resistance for PV modules is defined at $40M\Omega/m^2$ [14]-[15]. Consequently the total insulation resistance to ground of each PV string is inversely proportional to the number of PV modules connected in series [5], [16]. To this extent, the high voltage level appearing on a series string in conjunction with insulation resistance limitations entails an inevitable flow of DC leakage current. In particular, the study reported in [6] states that under normal operation conditions the estimated maximum leakage current from crystalline Si PV modules could reach 11μA/kW per module in 500-kWp array operating at 600Volts. That is, within [6], the cumulative total leakage current from the 500-kWp array is reported to be about 56mA.

However, the total magnitude of DC leakage currents in a PV system should be also associated to the insulation properties of materials (e.g. cables, inverter circuitry) - which can be limited and difficult to estimate under field conditions. To this end, and in order to limit leakage currents to an acceptable level, class II equipment with double or reinforced insulation is used quite frequently [3] in PV installations. Various international standards define what the minimum insulation resistance requirements are for PV modules [14], [15] and PV cables [17]. Additionally, the international standard referenced in [7] denotes the general requirements of PV inverters and explicitly defines their insulation specifications.

Nevertheless, it should be born in mind that DC leakage currents will inevitably increase with PV system size, as the system ages or in the event of unidentified DC ground faults.

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C. PV Ground Faults and Detection Mechanisms

In PV systems, DC leakage currents to ground may be sourced: a) by virtue of the distinct potential of the system against ground and/or the potential difference between active system elements [5], [6], [16] and b) from DC ground faults [18] [19]. Ground faults in PV systems occur when there is an unintentional connection between any current-carrying conductor with a grounded surface or earth. Faults on the DC side can be found in both grounded and floating PV systems. The detection mechanisms of these faults depend upon the DC grounding characteristics and are inevitably different for grounded and floating configurations.

1) Leakage Currents and DC Faults in Grounded PV Systems

In grounded PV systems, it is possible to have DC leakage current to frames emanating from the PV modules. This is an unavoidable phenomenon comprising very minor amounts of current leaking from the cells to the module frames [6], [16] and may be significantly increased due to degraded sealants and water ingress [3], [5]. More explicitly, the leakage current flow is exacerbated when moisture penetrates the module glass and as a result the resistance, between the active module circuitry and the frame, diminishes. Since the frame is grounded, the leakage current moves from the frame to ground circuit and return via the grounded polarity conductor and/or through the ground to the inverter modules. The location and number of inverters will vary, but for most large-scale PV systems, the DC wiring is distributed within a field resulting in significant length of cable (this can be estimated at 2.5 km in a 1MW PV plant). Damage during installation could generate a fault and it is also possible to have DC leakage currents from those portions of DC cables that are laid underground (e.g. cables between combiner boxes and inverter). This latter type of leakage will become more apparent in case of ground faults that can happen when the insulation of buried DC wires is ineffective or deteriorated due to moisture ingress, freeze/thaw cycles or accidental damages. In such cases, the leakage currents will flow through the earth or other conductive paths before returning back to the energy source - also through the grounded polarity conductor (see Fig. 3a).

For detecting DC leakage faults in grounded PV systems (mostly used in USA) the UL 1741 [11] and the NEC [12] require the installation of a Ground Fault Protection Device (GFPD). These devices are designed to interrupt the flow of DC fault currents and also to alert about fault occurrences. To visualize the current detection process, one should recall the fundamental grounding configurations of a grounded PV system that is shown in Fig.1. For example, if the negative current carrying conductor is grounded, this implies that the negative conductor has a connection to the grounded parts of the PV system through a fuse-type GFP device that is embedded in the inverter. If there is a fault (e.g., excess current leakage between a grounded conductor and ground), the fault current will flow from the fault location in a parallel ground circuit or via the earth, through the GFP fuse and back through the negative conductor to complete the circuit (Fig.3a). The magnitude of the fault current, returning through the GFP device, will be largely dependent on the impedance path formed by both the fault and earth return path. Generally, high ground fault impedance would result in lower ground fault currents flowing in the ground circuit return paths and this may limit the type of fault that can be sensed by the GFP device. A ground fault current that falls below the detection level of GFP devices may subsequently lead to a permanent reduction of operation output [19], which could provide an indication of the fault occurrence, if the power monitoring systems have adequate sensitivity.

However, once the GFP fuse's current rating is violated, the fuse will blow to isolate the system ground. To this extent, the selection of the fuse rating should be high enough to avoid nuisance tripping due to leakage and transient currents but not as high as to let harmful leakage currents undetected [18]. The ground fault interruption requirements and thresholds for grounded PV systems can be found specified in the UL 1741 [11]. The level of current thresholds tabulated in the standard is given according to the size of PV systems and respective size of the inverters (Table I).

TABLE I
GROUND FAULT DETECTION THRESHOLDS (UL 1741)

Inverter DC Rating (kW)	Ground Fault Current Threshold (A)
0 - 25	1
25 - 50	2
50 – 100	3
100 - 250	4
> 250	5

The thresholds shown in Table I are partly dependent on: a) the anticipated leakage currents from PV arrays and cabling under normal operating conditions and b) the contribution of other factors in the ground leakage detection processes, such as AC noise, radio frequency noise within the array and inverter [6]. However, it should be appreciated that these standardized thresholds are universal for all PV systems, regardless of their individual technical specifications and installation/location conditions. Thus, they should be regarded as conservative figures to avoid catastrophic fire failures. The currently applied detection thresholds may prevent to a large extent "nuisance" trips from regular and transient leakage currents which are possibly fueled by harsh environmental/soil conditions. Nonetheless, there is always the underlying risk that the inverters maintain the normal operation of a PV system, despite the presence of a considerable amount of leakage current flowing to ground [2], [6], [18].

2) Leakage Currents and DC Faults in Floating PV Systems

As previously noted in Section II, a floating DC system may have galvanic isolation between its DC and AC side or alternatively it may be non-isolated. The galvanic isolation is achieved by the use of isolation transformers compliant to the minimum insulation requirements - defined by the leakage current testing endeavors (for fire and shock hazards) described in [7]. Moreover, it is important to acknowledge that floating systems are not ideally isolated from ground due to the presence of resistive leakages paths to ground and distributed capacitance between active elements (PV modules, positive - negative DC wiring) and ground [13], as will be further explained in detail.

By definition, a floating isolated PV system does not have a distinct potential to ground. However, it is still possible to have DC leaking from the cells to the grounded metallic parts of the system. This leakage may be driven by the potential difference that arises between two remote active elements; for example the first and the last panel of a PV string. Furthermore, DC leakage activity can also take place where buried underground DC cables are laid due to their inherent potential difference (i.e. current from positive conductor to negative conductor) and/or deteriorated insulation properties.

In fact, the DC leakage activity in the cable circuitry of a floating isolated system, may exhibit the illustrative behavior shown in Fig.3b. Take for example the DC leakage activity in a floating, positive buried DC cable emanating from a combiner and leading to a central inverter. The solar irradiation dependent PV current flows through the modules and through the cable. It therefore produces a rise in the cable to earth potential which in turn results in leakage currents to ground. The leakage activity may be higher in those sections of buried DC cables that are faulted or have deteriorated insulation. Hence, under a specific PV current flow, the voltage will appear on the "floating" cable as some positive value to remote earth near the central combiner and as the same but negative value to remote earth near the inverter [20]. A positive voltage implies a current leaking out of the cable whereas a negative voltage implies a current leaking back into the cable, thus completing the current return path. At midpoint down the cable, the voltage to remote earth will be virtually 0 V [20].

Special attention, however, should be given in floating PV systems that have no galvanic isolation (i.e. non-isolated) where even the first ground fault in a PV array can create a hazardous potential [10]. This is because the fault or leakage current is allowed to be sourced on the AC side of the system [10], as illustratively shown in Fig. 3c. (Note: the grounded neutral on the AC side will provide a return current path for the fault current). Thus, a floating non-isolated PV system will have a reference potential to earth provided by the ac neutral that is grounded [2]. Therefore, the magnitude of the potential between the PV array and ground will be influenced by the topology and the switching operation of the inverter [21].

The above described principles dictate that both the ground fault tolerance practices and the detection of DC leakage currents are inevitably influenced by whether a PV system is galvanically isolated or not [7].

Primarily, ground fault detection in floating PV systems (isolated & non isolated) is typically achieved by monitoring the DC insulation resistance from the PV input (array) to ground [7]. The measurements are typically achieved by monitoring the insulation impedance of each pole (positive and negative) relative to ground [3], [5], [6], [16] as shown in Figs 3b and 3c. They are achieved by the use of embedded insulation monitoring devices (IMDs) [22] and they usually take place before inverter starts operation [7]. This type of monitoring is commonly referred to as R_{ISO} measurements. The IMD set point should be in accordance to the minimum insulation resistance of PV array under some worst meteorological conditions to avoid nuisance tripping events [3], [18]. The minimum permissible value of insulation resistance is defined in [7] and its dependence on the maximum array voltage (V_{max}) is given in (1).

$$R_{ISO\_\min} = \frac{V_{\max}}{30mA}\Omega \qquad (1)$$

However, a clear distinction between the floating isolated and non-isolated PV systems should be made when it comes to IMD measurements, as follows. Firstly, it should be borne in mind that in floating isolated configurations a single ground fault will not cause fault currents to flow, but a second ground fault in conductors will allow fault currents to circulate through the circuits associated with the two faults - i.e. due to the potential difference established between the faults' location [6], [13]. In floating isolated PV systems, a leakage activity to ground can be detected when the measured impedance to ground of either the positive or the negative conductor pole drops to a low level (faults of about one kΩ or less can be almost certainly detected by the IMDs). The inverter should indicate a fault; however its operation would not necessarily be prevented [7].

In floating non-isolated systems, if the IMDs detect a fault (i.e. low insulation resistance) the inverter should indicate a fault and would prevent its operation (i.e. not connect to the mains) because even the first ground fault will cause large fault currents to flow (due to the fact that the system is effectively grounded, by virtue of its non-isolating nature, via the AC side/grid). In such systems, it is therefore advocated to include an array residual current detection mechanism that would trip the inverter to automatically disconnect from the mains: a) in the event of a fault on the DC side that is not detected by the IMD or b) in the event of a fault that may appear during the operation of the inverter - (Note for (b): IMDs' measurements are obtained before the inverter starts its operation).

The use of a residual current detection mechanism is considered adequate since, as noted above, the fault current is allowed to be sourced on the AC side through the grounded neutral on the AC side. This transition of current on the AC side can create an imbalance in current going in (neutral) as opposed to the current going out (AC line conductors that are routed to substation) of the inverter. Therefore, the formed imbalance will indicate the presence of faults within the inverter as well as any ground faults (i.e. leakage currents) occurring in the DC side of the system.

The residual current detection mechanism could be an RCD (residual current device) with an interruption threshold setting of 30mA, located between the inverter and the mains. A type B RCD is required in order to respond to both residual sinusoidal alternating currents and residual direct currents [23]. Alternatively, in order to avoid unwanted trips, the inverter could benefit from an array Residual Current Monitoring Unit (RCMU) that is capable of detecting: a) continuous excessive residual currents and b) the sudden changes in residual currents. The RCMU shall measure the total RMS current of both ac and dc components. It should be noted that the thresholds for excessive residual currents are dependent on the inverter's size (e.g. 300mA rms for inverters with rated continuous output power ≤ 30 kVA). These are reproduced from IEC 62109-2 [7] in Table II and are meant to indicate that beyond these values, a major failure risk such as fire-ignition risk is highly probable.

TABLE II
IEC 62109-2: GROUND FAULT CURRENT INTERRUPTION THRESHOLDS FOR FLOATING (NON-ISOLATED) PV SYSTEMS

Description	Threshold Currents
For Inverters with rated continuous output power ≤ 30	300 mA rms

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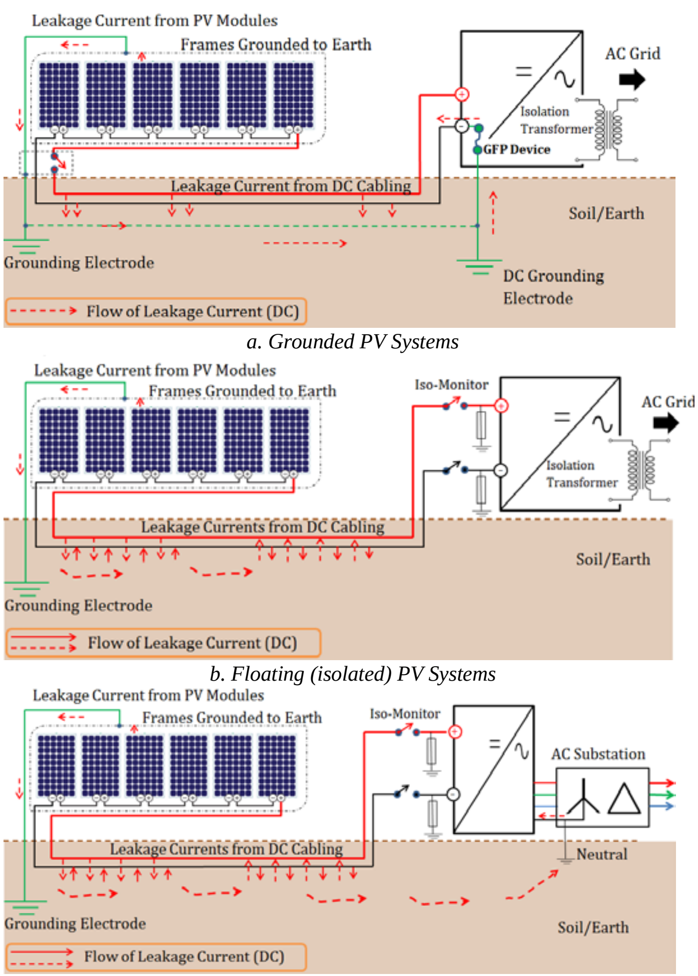
kVA	
For Inverters with rated continuous output power > 30 kVA	10 mA rms per kVA rated continuous output power

The threshold for excessive residual currents during the operation of the inverter (i.e. 300mA) is inevitably higher than the 30mA threshold used to determine the minimum acceptable value of R_{ISO_min} in (1) - applied before the inverter is set to operation. This is because during the operation of the inverter there is additional leakage current activity through the inverter [16] and cables [17]. It is also possible to have "normal" capacitive leakage currents flowing through distributed capacitances formed between the solar cells and the grounded metallic frames [21], [24]. In fact a floating non-isolated (i.e. transformerless) system could suffer from noticeable capacitive leakage currents. This is due to the lack of galvanic isolation, a fact that allows for a variable voltage level between the DC PV array and ground. That is, while the DC side of the PV array is floating, its voltage relative to the AC ground fluctuates by virtue of the inverters' high frequency switching process. In a floating isolated (with transformer) PV system capacitive leakage currents are negligible because the system is galvanically isolated. Thus any circulation of leakage currents between the ac and dc side of the inverter is avoided. It should be noted that no flow of capacitive leakage currents are anticipated in grounded PV systems, since the voltage of the DC PV array relative to ground is stable [13].



a. Grounded PV Systems

b. Floating (isolated) PV Systems

c. Floating (non-isolated) PV Systems

Fig. 3. DC Fault/Leakage Currents Paths

IV. Blind Spots Leading to DC Stray Current Corrosion

A. Introducing the Concept

So far the ground fault "*blind spot*" in grounded PV systems has been used to describe the presence of undetected ground leakage currents (i.e. faults on grounded conductors) that can result in some sort of arcing or ignition should a subsequent ground fault occur on an ungrounded conductor of the PV system. The Solar America Board for Codes and Standards (Solar ABCs) [1], [6] has described the "*blind spot*" problem as "*not an inherent limitation in the grounded/isolated configuration but rather an unintended consequence of the prevailing Ground Fault Detector/Interrupter (GFDI) method used to deal with multiple faults*".

At the same time, the board has correctly acknowledged that the so called "*blind spot*" phenomenon (i.e. ground fault in the grounded conductor) is not applicable in floating isolated systems since they have no grounded current-carrying conductors. However, excessive leakage currents due to various faults do exist in both grounded and floating configurations and if they are left undetected or unattended may facilitate serious failures in either of the two configurations.

To this extent, the leakage current detection thresholds tabulated in the UL 1741 [11] and in IEC 62109-2 [7] are set to protect the PV systems against serious failures. Nevertheless, the conclusion that can be drawn is that any dc leakage activity that falls below these thresholds (see section III-C) may go undetected by the protection devices or mechanisms. Apparently, there will be no problem for disastrous failures if the fault level remains below the recommended threshold settings. However, should we, under certain conditions, worry about DC stray current corrosion that can happen in underground metallic structures that are laid nearby a large scale PV system? More explicitly, are there any stray current DC corrosion blind spots?

It is worth reiterating at this point that stray current corrosion refers to corrosion damage resulting from direct current (DC) flow other than in the intended circuit. The first prerequisite to facilitate stray current corrosion is a ground fault that falls within the undetected threshold zones defined by the inverters (see section III-C). The second prerequisite is, for the faulted leakage current flowing into the earth to be persistent.

At this point, it should be noted that when considering stray current corrosion the location where the current first enters the ground will most likely be the PV module frame or buried cabling, where the insulation is damaged. If the damage is severe, rapid failure would be expected. Stray current corrosion at secondary locations is also possible. Large scale PV plants are often installed in rural areas and many such sites are remote from buried utility services, however the sites may be near to metallic infrastructures, such as national networks of buried gas and oil pipelines, or even irrigation pipelines. To this end, let us consider the case where a faulted DC buried cable (that may act as the source of stray leakage current into the soil), shares a parallel corridor with some buried metallic infrastructure (e.g. gas pipelines) located within or near the PV plant. It is high probable, the a proportion of the stray leakage current from the faulted DC cable is picked up on the nearby metallic infrastructure and travels for some distance before discharging back to the soil, to subsequently return back to the energy source. The latter rationally assumes that the stray current will attempt to return to the energy source through any low-resistance paths that exists within the soil. An analogy to the principle described above can be found in the Stray Current Control and Corrosion literature related to DC Mass Transit Systems [25]-[29]. These low resistance paths can be inherently given by metallic structures, especially when these structures are bare or not perfectly insulated. Thus, severe damage can occur on the metallic structures at the location where the current discharges back to soil for its return to the energy source.

More explicitly, the mechanism of stray current corrosion in large-scale PV applications can be briefly summarized as follows: The leakage current (from PV modules and buried DC cables experiencing a fault or deteriorated insulation) will flow into the soil and may subsequently flow along parallel circuits either directly through the soil or through buried metallic structures, before returning back to the energy source. To this end, a current loop is formed. Thus, any nearby metallic structures that provide a convenient (mainly) parallel conductive corridor can be very good candidates to provide a path for ground-fault leakage currents to return to the energy source. Given that current flow in a metallic conductor is electronic, while that through electrolytes such as the soil, concrete, etc., is ionic, it follows that there must be an electrochemical reaction (involving either ion to electron transfer as current enters a metallic conductor or electron to ion transfer as current discharges to earth) [30]. Therefore, where a current leaves metallic-pathways to earth (i.e. to return to the energy source) there will be an oxidation, or electron- producing, reaction. This reaction is visible after time as corrosion damage (1).

$$Fe \rightarrow Fe^{2+} + 2e^{-} \qquad (1)$$

Accelerated corrosion on metallic objects will, hence, occur from each point that current transfers from a metallic conductor to an electrolyte. One should note that for pipelines or structures with cathodic protection applied, stray current may not always generate corrosion, and low levels of interference may be tolerated.

The above conceptual analysis dictates that it is equally important to consider/examine the dc leakage currents return path to the energy source, in both grounded and floating PV Systems configurations.

B. Further Particulars for Grounded PV Systems

As previously described in Section III, in grounded PV systems, it is possible to have DC fault/leakage current to frames emanating from the PV modules. It is also possible to have DC leakage currents from those portions of DC cables that are laid underground and are connecting for example any combiner boxes to the inverter. This type of PV system is usually grounded through the use of Equipment Grounding Conductors (EGCs) [12] which ensure that all metallic infrastructures (e.g. frames, metal frames, conduits, junction boxes, and inverter) are equipotentially bonded.

Thus, any leakage current flowing to ground should ideally be captured by the EGCs and should return via the grounded polarity conductor to the modules. However, the conductive ability of the EGCs may be limited or deteriorated by a number of factors such as: a) loose joints, b) resistance increase of grounding connections due to galvanic incompatibility and thus corrosion of different metals (e.g. modules, rails, grounding conductors), c) damp heat aging, d) salt mist aging and e) mechanical damage or failure of EGCs.

Under these conditions, it is highly probable that some portion of the leakage current will attempt to return to the energy source through any other low-resistance paths that exist in the nearby vicinity. For example, through the soil and metallic structures. Therefore, DC corrosion damage may occur on the metallic structures at locations where the current discharges back to the soil for its return to the energy source. The concept described is shown in Fig. 4a. It is noted that Fig. 4a should be regarded as merely illustrative and the direction of stray current flows indicated by the arrows is a simplistic illustration to visualize the concepts verbally explained.

C. Further Particulars for Floating PV Systems

It should be reiterated from Section III that DC leakage currents are also present in floating systems due to the presence of resistive leakages paths to ground (i.e. between the PV array and ground).

The extent of DC stray current corrosion concern in floating PV system configurations will be dictated by the current return path to the energy source which in turn depends on whether the system is galvanically isolated from the AC side or not. In isolated floating PV systems the leakage currents may emanate both from the modules or the underground portions of DC cables (which have finite insulation) and will circulate through the soil and buried metallic infrastructure, as shown in Fig. 4b by means of a merely illustrative example.

The issue of leakage current flow from floating isolated PV systems can be exacerbated when the impedance formed by the circuit associated with a double fault is high. This condition may allow for a persistent flow of undetected (by IMDs) but corrosive leakage current to the earth.

Moreover, in floating PV systems (non-isolated) one should bear in mind that some DC leakage current would be allowed to return to the source via the AC side through the grounded neutral on the AC side (i.e. substation) as shown in Fig. 4c . If the substation is remotely located then the leakage current flowing into the earth may travel a considerable distance to reach the grounding neutral of the substation to close the loop.

It is therefore more probable to use any metallic low-resistance paths (e.g. pipelines) that exist in the nearby vicinity, thus increasing the risk of stray current corrosion of these metallic paths at the location where the current will discharge to flow in the grounded neutral of the substation.

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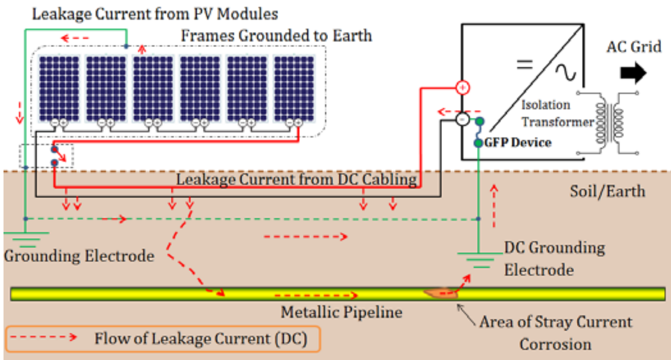
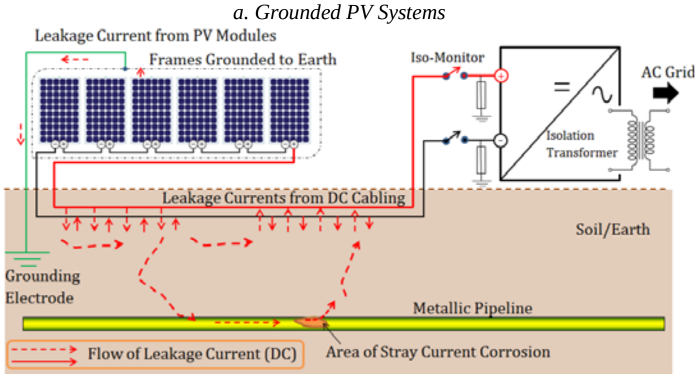
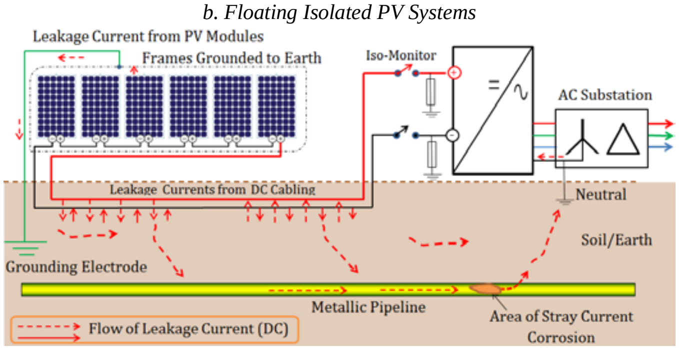


a. Grounded PV Systems



b. Floating Isolated PV Systems



c. Floating Non-Isolated PV Systems

Fig. 4. Graphical Illustration of Stray Current Corrosion

D. Towards Quantifying the Corrosion Impact

The impact of stray current corrosion has been thoroughly assessed in DC traction systems (EN 50162 [31] & EN 50122-2 [32]) and a fair analogy can be drawn when assessing the impact resulting from large PV plants. Stray current interference from DC traction systems is characterized by repeated relatively short duration fluctuations, with rapid corrosion potential changes. Any interference from solar farms is more likely to be associated with the intrinsic characteristics of PV current generation, with affects over a longer time period.

Calculation of metal loss arising from stray current leakage is determined from Faraday's laws, which for steel give a relationship that 1 amp.year of current will corrode approximately 9.1kg (for lead the value is 33 kg). The above relationship implies that a constant flow of 20mA DC would corrode 0.18kg of steel in the course of a year. This amount of metal loss, if restricted to a localized area, could result in the loss of pipeline integrity. These figures highlight the severity and risks of the issue for unprotected assets. Such risks are at their highest in locations where there are densely-packed buried utility services.

In PV installation industry, any DC leakage-related research efforts have been merely concentrated in demonstrating and characterizing the ground fault detection blind spots. The ultimate objective of these ongoing efforts is to reduce PV systems' susceptibility to legitimate DC ground faults. However, to appropriately calibrate the settings of the monitoring devices to detect legitimate faults entails understanding of the typical leakage currents' level under normal operating conditions. In many occasions, however, the owners of utility-scale PV systems are concerned about lost production from false detections or "nuisance" trips from regular and inevitable leakage currents. For this reason, a common practice followed by the owners is to raise the current leakage detection thresholds higher, to maintain their systems' operation and availability. In fact, their most preferred option is to respond to a detected fault by triggering an alarm rather than immediately seizing the operation of the inverter. This practice, however, suggests the sustained operation of the inverters in the presence of non-zero ground faults, which further entails the constant flow of leakage currents through unintended return paths through the soil or other conductive pathways.

To assess the stray current corrosion concern further, let us consider the standards' DC leakage detection thresholds for grounded and floating PV systems (described section III-C). In a 300kW PV system for example, the fault current detection threshold to prevent catastrophic failures is 5 A, if the system is grounded. On the other hand if the system is floating the threshold is approximately 30 mA (R_{ISO} measurement dependent) before the inverter is operating, reaching the value of 3000mA (in case of non- isolated PV systems) during the operation of the inverter. To this extent, we note that a practical criterion for characterizing the corrosion on metallic infrastructure "moderate to high" is for the estimated corrosion penetration rate to be approximately 10-100μm/year [33]. This penetration range corresponds (according to Faradays' electrolytic law for Fe) to corrosion current density, at the discharge location, that ranges from 0.001 to 0.01 mA/cm^2. Nonetheless, the up to date threshold levels of the leakage current detection devices for both floating and grounding PV systems are only calibrated to detect faults that their magnitude may exceed some hundreds of milliamps as discussed in the 300 kW example above. The latter implies the presence of undetected faults/ leakage currents that may result under certain conditions, in DC stray current corrosion on metallic infrastructure that is laid nearby large scale PV applications.

To this end, the work reported in [20], lists as the first attempt in the archived literature to approach the macroscopic impact of Photovoltaic oriented DC stray current corrosion on large scale solar farms' grounding and nearby third-party infrastructure. It unfolds by holistically defining the origin of the problem, modelling the problem in commercially available software and discussing the arising implications. The referred work highlights that the extent of stray current corrosion damage would be specific to the characteristics and topology of each large scale PV installation. It will also be specific to the relative position of any metallic infrastructure with respect to the faulted sections of the PV system. It may thus become the obligation of system operators to consider the stray current impact of a new or existing PV system, both in terms of damage to the PV installations and, if located in the vicinity of buried utility assets, the possible detrimental impact on those assets. Liaison with the utility company is needed to assess the risk, perhaps including measurement and monitoring and then selection of appropriate mitigation measures as needed. The PV operator may have to consider the cost of increased infrastructure's inspections and retrofit monitoring devices against the potential cost and damage from DC corrosion.

V. Conclusion

The recognition of the impact of DC stray current corrosion from DC traction projects has forced stakeholders across the world to consider a variety of design specifications, codes of practice and international standards to ensure stray current interference is minimised. Such codes and standards are intended to provide designers and utility companies with a corrosion management strategy that defines a level of corrosion risk which is acceptable across infrastructures. The utilization of existing documentation or development of similar corrosion management systems and practices may be necessary for PV plant owners and Distribution Network Owners.

One should note that a typical useful life-cycle of commercial PV systems is around 25 years. Thus, system designers and contractors should ensure a similar life-cycle for the grounding and supporting infrastructure of these systems and at the same provide evidence that reasonable efforts are made to prevent damage to third-party utility services in areas near the PV plants. Towards achieving these targets it may be necessary for relevant code of practice standards to be revised to further address the blind spot susceptibility arising from current detection practices. This may entail products that include more sensitive ground fault detection mechanisms that can be smoothly embedded in PV array isolation measurements as well as specialized audits at regular intervals. In cases where the level of stray current cannot be controlled to acceptable levels, measurement and monitoring of the third party assets may be required, with mitigation applied to the affected structure if required.

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