Guidelines for Protection Against Electric Shock in PV Generators

Jesus C. Hernández and Pedro G. Vidal

Abstract—This paper assesses the protection against electric shock in a photovoltaic generator (PVG), the dc side of a PV installation. Within this context, we discuss the applicability of the protection requirements of the International Electrotechnical Commission 60364, the international standard that provides guidelines for wiring in low-voltage (LV) electrical installations. The unique operational characteristics of a PVG, which differ from those of a conventional ac LV system, made it necessary to revise and adapt these requirements. With a view to discovering the effectiveness of electric shock protection in ungrounded PVGs, we carried out both a theoretical and practical study in a real PVG in order to analyze its electrical behavior. As part of our study, the feasibility of applying an “active” means of protection was experimentally tested in this same PVG.

Index Terms—Electric shock, grounding, insulation, International Electrotechnical Commission (IEC), leakage currents, photovoltaic (PV) power systems, protection, safety.

I. INTRODUCTION

Ensuring safety in photovoltaic (PV) installations is an important issue, which must first be resolved if this technology is ever to be applied on a larger scale. PV installations should have the following types of protection: 1) protection against electric shock; 2) fire protection; and 3) lightning and surge protection. Our research study specifically targets protection against electric shock. Electric shock protection is crucial due to the increasing number of potential electrical hazards in PV installations as a result of their size and proximity to population centers.

Nevertheless, despite its importance, electric shock protection in PV generators (PVGs) has not been widely addressed. In the 1980s, Key and Menicucci [1] described the practical problems that initially arose in the application of the National Electrical Code to PVGs. In the 1990s, the personal safety levels of grounded and ungrounded PVGs were compared [2]. Subsequent studies proposed double insulation or extra-low voltage (LV) as a means of protection [3], [4]. Wiesner et al. [5] suggested the use of insulation monitoring devices (IMDs). Finally, Vidal et al. [6] proposed the automatic disconnection of the electricity supply in ungrounded PVGs. Generally speaking, however, field experience in this area is limited, and protective guidelines and provisions are not uniform.

Electric shock protection is possible only if requirements are met at both system and equipment levels.

At the system level, protection against electric shock in conventional ac LV systems is regulated by the electrotechnical requirements defined in international standards International Electrotechnical Commission (IEC) 61140 [7] and IEC 60364-41 [8]. These requirements are based on decades of scientific progress and practical experience, and have evolved in consonance with technical knowledge and advances.

In this sense, PVGs are still in the initial stages of this process because this type of technology is relatively new; and also because of their unique operational characteristics [1], [4]–[6].

NOMENCLATURE

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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<tbody>
<tr>
<td>$C_{LEK}$</td>
<td>Leakage capacitance of a PV generator.</td>
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<tr>
<td>$C_{LEK,m}$</td>
<td>Leakage capacitance of a PV module.</td>
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<tr>
<td>$F$</td>
<td>Parameter equal to $R_p/R_s$.</td>
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<tr>
<td>$i_H(t)$</td>
<td>Transient body current.</td>
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<tr>
<td>$I_d$</td>
<td>First fault current between live conductor and exposed conductive part.</td>
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<tr>
<td>$I_{H(p)}$</td>
<td>Peak maximum value of the discharge of a capacitor on the human body.</td>
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<tr>
<td>$I_L$</td>
<td>Steady-state touch current limit.</td>
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<tr>
<td>$I_{LEK}$</td>
<td>Leakage current of a PV generator.</td>
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<tr>
<td>$I_{Δn}$</td>
<td>Rated residual operating current.</td>
</tr>
<tr>
<td>$R_n$</td>
<td>Specified response value.</td>
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<tr>
<td>$R_A$</td>
<td>Ground electrode resistance of the equipment grounding.</td>
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<tr>
<td>$R_{HB}$</td>
<td>Resistance of the human body.</td>
</tr>
<tr>
<td>$R_{ISO}$</td>
<td>Insulation resistance of a PV generator.</td>
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<tr>
<td>$R_{ISO, PER}$</td>
<td>Safety threshold of the $R_{ISO}$ in permanent regimen.</td>
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<td>$R_{ISO, TR}$</td>
<td>Safety threshold of the $R_{ISO}$ in transient regimen.</td>
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<tr>
<td>$R_p$</td>
<td>Parallel insulation resistance of a PV module.</td>
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<tr>
<td>$R_s$</td>
<td>Series insulation resistance of a PV module.</td>
</tr>
<tr>
<td>$U_I$</td>
<td>Conventional touch voltage limit.</td>
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<tr>
<td>$U_{OC, PVG}$</td>
<td>Open-circuit voltage of a PV generator.</td>
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<tr>
<td>$\tau$</td>
<td>Discharge time constant.</td>
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Subscripts

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<td>MAX</td>
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<td>MIN</td>
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Acronyms

<table>
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<th>Acronym</th>
<th>Description</th>
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<tr>
<td>ECPs</td>
<td>Exposed conductive parts.</td>
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<td>IMDs</td>
<td>Insulation monitoring devices.</td>
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<td>LV</td>
<td>Low voltage.</td>
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<td>PVGs</td>
<td>Photovoltaic generators.</td>
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<td>RCMs</td>
<td>Residual current monitors.</td>
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As part of the Univer Project [9], we analyzed the use of general protective provisions for ac LV systems in PVGs, and found that it was difficult to apply many of these provisions to PVGs precisely because of the way in which they operate. It is a fact that during the code-compliant design of electric shock protection for PVGs, various difficulties were encountered in the interpretation of protection requirements. This led to the subsequent development of PV-specific electrical codes and standards, at both an international level [10], [11] and local level: USA [12], [13] and Spain [14]. It is important to highlight that on the ac side of the PV installation, these guidelines can be applied without any problems [4], [6].

After analyzing these standards and reviewing previous studies [15], we made a systematic comparison of their contents. We found that such standards often show marked differences, and worse yet, reflect a wide range of inconsistencies. Responding to the urgent need for international harmonization, the work carried out by the IEC Technical Committee 82 targets the harmonization of guidelines for PV installations, which will doubtlessly be conducive to the wider use of this technology in the future.

Regarding the safety of PV equipment, a recent study shows how the most basic requirements are regulated by existing standards or by standards currently in development: PV modules [16], [17] and PV inverters [18], [19].

This paper begins by explaining the basic premises of electric shock protection as well as its safety levels for PVGs. This is followed by an in-depth description of protective provisions for PVGs. These provisions include PVG design practices as well as hardware recommendations. We also discuss how such provisions should be applied. We then describe the electrical behavior of a 68-kWp PVG of the Univer Project [19]. The data obtained were analyzed with a view to studying the effectiveness of electric shock protection in ungrounded PVGs. Lastly, we discuss the feasibility of applying an “active” means of protection, an option that was experimentally tested in our experimental PVG. Also analyzed are other crucial factors involved, such as the operating capacity and effectiveness of available hardware.

II. BASIC PRINCIPLES OF ELECTRIC SHOCK PROTECTION

The golden rule of electric shock protection is that hazardous live parts should not be accessible, and that exposed conductive parts (ECPs) should not be hazardous live either under normal, or under single-fault operating conditions.

Under normal operating conditions, protection against direct contact is required, and is provided by basic protection provisions. In the case of single-fault operating conditions, protection against indirect contact is likewise necessary, and is provided by fault protection provisions. Fault protection can be achieved by a further provision, which is independent of any basic provision, or by an enhanced provision that provides both basic and fault protection.

The effects of the shock current on human beings [20] were used as the basis for setting the requirements for electric shock protection in [8]. The conventional touch voltage limit $U_T$ is the most frequently used parameter in this type of protection. However, the current threshold of ventricular fibrillation can also be used as a protection level value. In what follows this value is referred to as the steady-state touch current limit $I_T$.

In ac LV systems, these limits are well known. However, in PVGs, which are outdoor dc electrical installations, such limits have not as yet been ascertained. Thus, according to [21], the value for $U_T$ in PVGs should be set at 75 V due to their potential water-wet operating conditions. Similarly, according to [20], the value for $I_T$ should be less than 135 mA. In our research study, we set $I_T$ at 100 mA.

III. PVG-ADAPTED PROTECTIVE PROVISIONS AGAINST ELECTRIC SHOCK

This section describes the optimal requirements for electric shock protection in PVGs. These requirements are the result of the modification, adaptation, or re-elaboration of the general requirements for ac LV systems [7], [8] as well as the more specific requirements for PV systems [10].

A. Combined Protection Against Direct and Indirect Contact

1) Protection by Extra-Low Voltage: This enhanced protective provision entails limiting the maximum operating voltage of the PVG to a safe value ($\leq U_T$). The PVG must also be safely isolated from the grid by a safety isolating transformer. The use of class III equipment [7] is obligatory.

2) Protection by Double or Reinforced Insulation: This enhanced protective provision is provided by the selection of suitable equipment. The construction of this equipment offers the necessary degree of safety regarding electric shock. The following types of equipment are possible: 1) class II equipment with double or reinforced insulation [7] and 2) equipment with a similar type of insulation, known as metal-encased class II equipment [11].

A PVG basically consists of general-purpose electric equipment with the exception of the PV modules. Nowadays, class II equipment or its equivalent is rarely used, except in the case of portable or semifixed appliances. As a result, the application of this protective provision to PVGs is difficult or extremely expensive. More specifically, it is still fairly uncommon to find LV conductors or LV switchboards and panel boards that meet class II safety requirements. In contrast, class II PV modules [16] are widely manufactured. Their use, which is recommended in [2] and [4] and obligatory in [11], is geared to eliminating insulation failures in PVGs.

However, applying this protective provision to PVGs is made rather difficult by the most frequent PV equipment grounding technique. Conductive equipment parts should not be bonded to ground since class II equipment becomes class I. However, PV modules are bonded to supporting structures that are normally grounded.

B. Protection Against Direct Contact (Basic Provisions)

Full protection against direct contact is afforded by the insulation of live parts or enclosures. In areas restricted to skilled personnel, barriers or suitable clearance can offer partial protection.
In case of the failure of basic protective provisions or user carelessness, additional protection can be obtained with a protective device (e.g., residual current devices in ac LV systems). Nevertheless, PVG operating characteristics, which differ from those of an ac LV system, make it necessary to use the protective devices listed later. In any case, the characteristics of such devices (i.e., their set points and maximum break times) should protect users against direct contact [20]–[22].

### C. Protection Against Indirect Contact (Fault Provisions)

The automatic disconnection of supply should be the general fault protective provision applied to any PVG. Supplementary insulation can also be used. However, for PVGs, IEC 60364-7-712 [10] forbids protection by nonconducting locations and earth-free local equipotential bonding.

1) **Protection by Supplementary Insulation:** This provision consists of a supplementary insulation to prevent any possible failure in the basic insulation.

2) **Automatic Disconnection of Supply:** This provision prevents a hazardous touch voltage in the PVG in case of failure in the basic insulation. Protection is ultimately provided by coordinating the type of grounding system of the PVG, the properties of its protective equipotential bonding, the tripping characteristics of protective devices, and the characteristics of class I equipment.

The types of grounding system in a PVG, according to [10]–[13] and [23], can be:

1) an ungrounded PVG (ungrounded live parts and grounded ECPs) and 2) a grounded PVG (live parts and ECPs grounded by means of a single ground electrode). A PVG with live parts and ECPs grounded in independent ground electrodes is not advisable for reasons of personal safety (see Section VIII), or lightning and surge protection [24].

As a general rule, the following requirements should be complied with in this protective provision.

1) In case of fault between a live part and an ECP or protective conductor, a protective device must avoid a hazardous touch voltage by disconnection.

2) Depending on the grounding system, ECPs must be properly connected to the designed protective equipotential bonding system. This system includes a ground electrode, protective conductors, and potential protective screening. Single-point connection between ground electrode and equipotential bonding is recommended in [11]–[13]. The requirements for ac LV systems, which have been adapted for PVGs are the following.

   **a) Specifications for a grounded PVG:**

   1) All ECPs must be connected to the system grounding (henceforth, PVG grounding) by protective conductors. The best point for ground connection is the dc input terminal of the PV inverter as suggested in [11]–[13].

   2) Preferably, negative live conductors must be grounded [11]–[13], [20]. PVGs with their center tap grounded are also allowed.

   The other requirements stated in IEC 60364-4-41 [8] for the ac LV system are not applicable to PVGs because of the difference between short-circuit currents in both systems.

   **b) Specifications for an ungrounded PVG:**

   1) Live parts of the PVG must be isolated from ground.

   2) ECPs must be collectively bonded by protective conductors to a ground electrode and the following conditions satisfied:

\[
R_A I_d \leq U_L. \tag{1}
\]

3) In the event of a first solid fault to ECP or ground, the fault current is low. This condition is neither dangerous for people nor harmful to the PVG if (1) is fulfilled. Thus, disconnection is not imperative.

4) The use of an IMD [25] is highly recommended, as mentioned in [2], [6], and [26]. Such a device warns of the appearance of a first fault, thus allowing its rapid localization and repair. This significantly improves PVG operability, due to preventive maintenance.

In the ac LV system, an insulation fault originates a high short-circuit current through the protective conductors, which signifies that ECPs can attain a hazardous potential. The proposal regarding protection only relates maximum allowed disconnection times to each nominal system voltage since a solid fault provides enough current to operate overcurrent protective devices.

In the PVG, an insulation fault causes a short-circuit current similar to the nominal current. Thus, the potential attained in ECPs is normally nonhazardous. For example, the usual low value of the protective conductor impedance (e.g., impedance ≤1.2 mΩ/m if its section ≥16 mm²) together with short connection distances to ground (usually ≤30 m) requires very high short-circuit currents (≥1650 A) to reach a hazardous touch voltage (>UL). Therefore, no requirements for protective devices are often necessary. The only possible requirement is a maximum time equal to 5 s to disable the PVG.

However, equipment safety requirements may demand the immediate disenablement of the PVG. Depending on its position (see Fig. 1), an insulation fault may lead to a PV inverter commutation fault.

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R_A I_d \leq U_L. \tag{1}
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4) The use of an IMD [25] is highly recommended, as mentioned in [2], [6], and [26]. Such a device warns of the appearance of a first fault, thus allowing its rapid localization and repair. This significantly improves PVG operability, due to preventive maintenance.
5) After the first fault, the protection requirements in the event of a second fault are those previously defined for the grounded PVG.

IV. APPLICATION OF THE PROTECTIVE PROVISIONS IN A PVG

The electric shock protective provisions for PVGs, according to [7] and [8], should be applied as follows:

Direct contact (basic protective provision):
1) protection by basic insulation of live parts;
2) protection by extra-LV;
3) protection by reinforced insulation of live parts.

Indirect contact (fault protective provisions):
1) protection by extra-LV;
2) protection by reinforced insulation of live parts;
3) protection by supplementary insulation of live parts;
4) protection by automatic disconnection of supply.

Since protective provisions 1–4 guarantee personal safety through PVG design (preventive provisions), these provisions are regarded as “passive.” In contrast, provision 5 is considered to be “active” because personal safety depends on devices that operate when risk scenarios appear. This risk is monitored by means of the control variable measured by the devices.

The choice of electric shock protection is determined by PVG size, location accessibility, skill level of maintenance team, cost of protective hardware, and PVG availability. These aspects as well as others [24] should also be considered in the definition of lightning and surge protection (other important safety issues). Consequently, it is necessary to agree on a safety design. When it is only a question of personal safety, the following options are possible.

A. Protection by Extra-LV (Protective Provision 2)

This enhanced provision is advisable for small PV power applications with an operating voltage limit value of \( U_L \).

B. Protection by Double or Reinforced Insulation of Live Parts
(Protective Provisions 1 + 4 or 3)

This enhanced provision is restricted to PV power applications under the effective supervision of trained and experienced personnel (restricted access area).

C. Protection by Basic Insulation Plus Automatic Disconnection of Supply
(Protective Provisions 1 + 5)

This combination of provisions is advisable for hazardous PV power applications with operating voltages higher than \( U_L \). The applications may be: 1) intermediate installations (residential, commercial, and industrial) with voltages of less than 600 V [12] and 2) multimegawatt power plants with higher voltages. In group 1), access to the installations is usually permitted and the maintenance team is composed of nonspecialized personnel. In group 2), access is always restricted to skilled or highly trained personnel in central plants.

The ungrounded PVG (the safer option) is recommended for crowded sites and installations with easy accessibility, whereas a grounded PVG is advisable in the case of areas with little traffic and nonspecialized maintenance personnel.

This combination of provisions requires the installation of various types of protective device, which have been itemized in terms of the type of PVG grounding involved. The specific detection levels of the devices and their most frequent location are also shown.

1) Elements of the Electric Shock Protection Device: Since the procedure used for the automatic disconnection of the supply in the ac LV system is not valid for PVGs [6], an alternative shutdown procedure must be used. (See section VII for a description.) This also makes it necessary to use other devices for electric shock protection in both systems.

In the ac LV system, this device contains two functional units [27]: a detection/evaluation unit of the control variable and a unit with an interruption function. A switching device performs this interruption function. However, in PVGs, this function must be carried out by the shutdown system. Accordingly, this type of protection device consists of a combination of devices, each with its own function, though all work together (Figs. 1 and 2). In other words, this device has a detection/evaluation unit (monitoring device), which, in turn, triggers another device that disables the PVG (shutdown system). This combination provides a sufficient level of personal protection [8], [27].

2) Protective Device in a Grounded PVG: The device that continuously detects/evaluates the fault/leakage current between live parts and ECPs or ground is a residual current monitor (RCM) [28], which is sensitive to dc currents, i.e., type B [29]. This monitoring device is installed in the grounding conductor of the PVG (see Fig. 1). The RCM triggers the shutdown system when the current exceeds its set point (see Fig. 8).

The installation of this device complies with the “active” protective provision formulated in Section III-C2(a). The RCM set point \( (I_{\Delta n}) \) must be consistent with the maximum leakage current of the PVG \( (I_{LEK MAX}) \) under any meteorological condition without insulation faults. In order to avoid unwanted tripping, the next set point should be chosen according to its
The value of the RCM set point must always be as small as possible to cover all potential insulation faults. The fault current (see Fig. 1) ranges from zero (point 1) to the short-circuit current of the PVG (point 2).

Additional protection against direct contact is obtained when the RCM set point permits adequate protection of this contact [20]. Thus, this set point must always be lower than \(0.5I_L\) (50 mA), in accordance with the previously mentioned tripping conditions.

3) Protective Device in an Ungrounded PVG: The device that detects/evaluates the insulation resistance between live parts and ground is an IMD. This monitoring device is set up between the negative terminal and ground (see Fig. 2). The IMD triggers the shutdown system when the resistance falls below its set point (see Fig. 8).

The installation of this device complies with the “active” protective provision formulated in Section III-C2(b). The IMD set point \(R_{an}\) must be consistent with the minimum insulation resistance of the PVG \(R_{ISO \ MIN}\) under any meteorological condition without insulation faults. In order to avoid unwanted tripping, the next set point should be chosen according to its allowed relative percentage error [25]

\[1.5R_{an} \leq R_{ISO \ MIN} \]  

Additional protection against direct contact is provided when the IMD set point allows this contact to be adequately protected [22]. This set point is obtained by means of the equations in Section V.

V. DIRECT CONTACT IN AN UNGROUNDED PVG

A. Theoretical Study

1) Transient Body Current: The PVG insulation is characterized by a leakage impedance spread throughout the dc grid, with resistance \(R_{ISO}\) and capacity \(C_{LEK}\) components. Under normal operating conditions, the range of values for every component consists of units of megohm and tens of microfarad, respectively. For instance, \(R_{ISO} \in [0.12, 4.6] \, \Omega\) and \(C_{LEK} \in [0.7, 42] \, \mu F\) in a real 68-kWp PVG [30].

The energy stored in the leakage capacitance of a PVG can significantly contribute to electric shock risk. Thus, a direct contact may trigger a capacitor discharge throughout the body due to the energy redistribution of the capacities. We evaluated this transient body current (see Fig. 3) in order to find out the protection level associated with the ungrounded configuration.

Fig. 3 shows the equivalent electric circuit model used to evaluate the transient body current in the event of direct contact with the positive terminal of a PVG. We have modeled the electrical behavior of the PVG insulation using the module model in [30]. The PVG insulation is evenly distributed.

The most hazardous contact occurs when there is zero contact resistance between feet and ground and a minimum resistance value of the human body \(R_{HB\ MIN} \approx 650 \, \Omega\) [20]. In this case, the fault resistance value is much lower than the individual minimum values of \(R_s\) and \(R_p\) of a PV module. Therefore, when determining the transient behavior of the electrical circuit, the fault resistance is regarded as negligible, and point A is bonded solidly to the ground. For example, a 106-Wp PV module has \(R_s > 0.01 \, \Omega\) and \(R_p > 0.1 \, \Omega\) [30].

According to this hypothesis, the theoretical transient body current \(i_H(t)\) is determined by using a classical approach to transient analysis in this first-order RC circuit

\[
i_H(t) \cong \frac{U_{DC,PVG}}{2(R_{ISO} + R_{HB})} \left[ 1 + \frac{FR_{ISO}}{(R_{ISO} + (1 + F)R_{HB})} e^{-t/\tau} \right].
\]

The discharge time constant \(\tau\) is given by

\[
\tau = C_{LEAK} \frac{(R_s R_p)}{(R_s + R_p)}.
\]

Equation (4) has been experimentally validated. Thus, Fig. 4 shows the theoretical transient body current, obtained from (4), together with the real measurement (simulated contact) in a 68-kWp PVG [9], operating under medium–low insulation conditions. The goodness of fit validates the equation proposed for the transient body current in the case of direct contact.

2) Insulation Threshold to Protect Direct Contact: The effectiveness of the protection against direct contact in an ungrounded PVG depends on its insulation resistance. High values reduce the transient and permanent body current, and consequently, the risk of electric shock.

In transient regimes, the safety threshold of the insulation resistance \(R_{ISO \ TR}\) is obtained by taking into account the effects...
of the capacitor discharge on the human body [22]. The threshold of ventricular fibrillation of this discharge \( I_{H(p)} \) must be lower than 1.22 A. In the adjustment of this threshold, the discharge duration (\( \approx 3\tau \)) is higher than 10 ms. In PVGs, however, the resulting duration is always longer (see following section). Once the threshold \( I_{H(p)} \) is set, \( R_{ISO\ TR} \) is obtained from (4). Nevertheless, (4) is previously adapted to the highest risk case for people, which is insulation that is oriented toward the terminal opposite contact and a minimum value of \( R_{HB} \) where

\[
i_H(t = 0^+) = \frac{U_{OCP\ PVG\ MAX}}{R_{HB\ MIN} + R_{ISO}/(1 + F)} = I_{H(p)} \leq 1.22.
\]

(6)

Therefore, \( R_{ISO\ TR} \) is given by

\[
R_{ISO\ TR} \geq (1 + F) \left[ \frac{U_{OCP\ PVG\ MAX}}{1.22} - R_{HB\ MIN} \right].
\]

(7)

In a permanent regime, when the energy redistribution stored in the leakage capacitance is carried out, the safety threshold of the insulation resistance \( R_{ISO\ PER} \) is defined by [6]

\[
R_{ISO\ PER} \geq 10U_{OCP\ PVG\ MAX} - R_{HB\ MIN}.
\]

(8)

In order to protect the transient and permanent regime, the highest threshold is always chosen. Usually, \( R_{ISO\ PER} \) determines this threshold. However, given the high values of the \( F \) parameter in the following section, if the PVG voltage is more or less higher than 850 V, the threshold is set by \( R_{ISO\ TR} \).

B. Transient Body Current Variation Due to Meteorology

The insulation of a PVG depends on meteorological variables such as relative humidity and ambient temperature [30]. Hence, the transient body current also depends on these variables according to (4). This section studies the influence of these meteorological variables on the remaining parameters related to the transient body current, namely, the \( F \) parameter and the discharge time constant \( \tau \). At the very least, knowledge of the quantitative variation of the previous parameters is essential since they determine the safety threshold necessary for protection from direct contact in the transient regimen.

The methodology used to study the behavior of these parameters is twofold. In our first analysis, we used transient body current tests in a real 68-kWp PVG [9]. The second analysis consisted of insulation tests on several PV modules in our high-voltage laboratory.

First, on various days from August 2001 until March 2007, the transient body current simulated was measured along with the following meteorological variables: relative humidity and ambient temperature. Fig. 5 shows the discharge time constant as a function of the relative humidity along two isotherms. Fig. 6 shows the \( F \) parameter at a constant relative humidity versus temperature.

Figs. 5 and 6 show that the meteorological variables have a significant influence on the parameters analyzed. In our continental climate, the \( F \) parameter reaches values up to 100 in the worst set of safety conditions (maximum transient body current). The discharge time constant \( \tau \) is always higher than 1 s.

The results obtained are directly related to the PV module used, according to its \( R_s, R_p, \) and \( C_{LEK\ m} \). For this reason, we decided to extend our study to other PV modules. We thus performed insulation measures on several PV modules in the temperature and humidity chamber of our high-voltage laboratory (see Fig. 7). Tests were performed under all likely meteorological conditions. The transient response of the insulation...
measurement [30] allowed us to determine the corresponding $F$ parameter and the discharge time constant $\tau$. These new results only showed slight behavioral differences in relation to the results in Figs. 4 and 5.

VI. PVG SHUTDOWN SYSTEM DESIGN

The shutdown system of the PVG (Figs. 8 and 9) short circuits and bonds to ground the live conductors at the inverter dc input. This guarantees that the voltage is switched off in the entire field of PV modules, thus eliminating the risk of electric shock [6]. However, the inverter should first be separated from the dc side so as not to damage the inverter.

VII. COMPARATIVE ANALYSIS OF ELECTRIC SHOCK RISK IN A PVG, DEPENDING ON THE TYPE OF GROUNDING SYSTEM

An ungrounded PVG offers full protection against electric shock (direct and indirect contact) whenever the insulation resistance of the PVG is above a certain safety threshold. However, an insulation failure to ground/ECP equals the risk level of a PVG with a grounded configuration. As previously mentioned, a grounded PVG with a single ground electrode (for the equipment and PVG grounding) eliminates the risk of indirect contact. A low resistance value of this ground electrode is not necessary since it has no influence on the risk. In the rare event of a ground fault, a low value is required to protect against indirect contact [6]. However, when two separate ground electrodes are used in order to eliminate the risk of indirect contact, a very low resistance value of the grounding equipment is required. This value is rarely reached in most installations. Therefore, this configuration is the one that is the least safe.

Protection against direct contact is provided by the previously mentioned protective devices in grounded and ungrounded configurations. However, there is a difference between both configurations. In grounded configurations, the protective device performs after contact occurs, whereas in the ungrounded one, the device performs before contact, thus avoiding a painful electric shock.

VIII. FEASIBILITY OF APPLICATION OF THE “ACTIVE” PROTECTIVE PROVISION IN A PVG

The design of an effective protection system against electric shock in PVGs of hazardous voltage must include a “passive” protective provision. However, an “active” protective provision is the only type that can avoid the effects of potential electrical accidents (e.g., carelessness of users, unexpected insulation failures, etc.).

The feasibility of applying an “active” protective provision in PVGs involves checking the operating capacity of the hardware available in the market and its effectiveness. Operating capacity means that the set point of the protective device must be consistent with the variation of its control variable due to meteorological conditions. Effectiveness signifies that the PVG is disabled within the specified response time to prevent the occurrence of hazardous touch voltage, in case of direct contact or insulation failure.

The following tests and measurements were carried out on a real PVG (68 kWp, 580 V) [9] to test the feasibility of applying this type of protective provision.

1) Measurement of the leakage current (grounded configuration) and insulation resistance (ungrounded configuration) over a period of six years in all possible meteorological conditions. The results of the first two years were presented in [30].

2) Measurement of the response time for PVG disablement in a grounded and ungrounded configuration.

As already explained, protection against indirect contact is not usually necessary in grounded PVGs. It is not necessary in ungrounded PVGs either if (1) is fulfilled. Thus, the “active” protective provision provides additional protection not only against direct contact, but also against indirect contact.

A. Measurement of the Leakage Current (Insulation Resistance) to Ground in a Real PVG

The field data collected confirm the operating capacity of the protective device against electric shock in grounded and ungrounded PVGs.

In the case of a grounded PVG, the value of the RCM set point must be 50 mA for additional protection against direct contact. According to (2), this set point was also consistent with the $I_{LEK \text{ MAX}}$ measured in our experimental PVG (3.7 mA) under all possible meteorological conditions. This provided additional
protection against indirect contact. This value is one of the highest expected values in PVGs of a similar size because of the high operating voltage ($\approx 600$ V) of our experimental PVG.

In the case of the ungrounded PVG, (1) is fulfilled. According to (8), the value of the IMD set point should be 5.15 k$\Omega$ to obtain additional protection against direct contact. This value is higher than the value obtained by (7) in this PVG. According to (3), this set point was also compatible with the $R_{\text{ISO MIN}}$ measured in our experimental PVG (100 k$\Omega$) under all possible meteorological conditions. Thus, additional protection against indirect contact was also obtained.

Generally speaking, if during the planning stage of a large PVG, it is divided into several PV arrays, with their corresponding protective devices, these devices should function perfectly well without any problems when the PVG is operating.

**B. Measurement of the Response Time to Disable a Real PVG**

In the case of a direct contact or a hazardous insulation failure, the PVG must be disabled. The time to disable the PVG can be defined as the sum of the response time of its monitoring device and its shutdown system. This section describes the standard requirements pertaining to the response time of the monitoring devices and shutdown system. Finally, it presents measurements that prove the effectiveness of the hardware.

In grounded PVGs, the RCM standard [28] establishes a response time similar to that of the protective device against direct contact in ac LV systems [27]. In ungrounded PVGs, the IMD standard [25] establishes a response time that can vary, depending on the system leakage capacitance ($<100$ s if this capacitance is equal to 1 $\mu$F). However, different manufacturers guarantee up to 200 s for a higher capacitance ($\leq 100$ $\mu$F). This is the most frequent case in PVGs [30].

The response time of the shutdown system is less than 0.1 s, based on the requirements in standards [31] and [32]. This time includes the consecutive operation of the circuit breaker (C1) and the circuit breakers/contactors (C2) (see Fig. 8). Therefore, the disablement of the PVG only adds up to 0.1 s in relation to the response time of its corresponding monitoring device.

These standard requirements prove the effectiveness of the hardware targeting protection against direct contacts in grounded and ungrounded PVGs. Thus, in grounded PVGs, the operating characteristics of the protective device (RCM plus shutdown system) are compatible with the requirements in [20] for protection against direct contacts in dc installations. This means that hazardous electric shock is prevented whenever the body current is less than 0.35 A (most cases). In ungrounded PVGs, the disablement of the PVG occurs 200.1 s after a fault. In this short time period, just after a failure, the probability of direct contact is very low, and so, total effectiveness is almost achieved.

These standard requirements once again prove the effectiveness of the hardware available for protection against indirect contacts. Thus, after a first solid fault, the maximum response times to disable the PVG are 0.14 s for grounded PVGs and 200.1 s for ungrounded PVGs. These values are consistent with those in the standard [8], which are 5 s and a nondefined time.

The effectiveness of the hardware was also checked in our experimental PVG by means of various simulations in which the response time was measured. First, we simulated extreme risk situations of direct contact [6] in a grounded configuration. A 650-k$\Omega$ resistance was used as the most unfavorable $R_H$ [20]. The results obtained showed suitable response times for PVG disablement, which prevented the occurrence of hazardous electric shock in all dangerous simulations [20]. Finally, in an ungrounded configuration, failure simulations, both of the evenly distributed and localized variety, were also carried out. The value of the fault resistance considered was less than the IMD set point. The results showed that response times for PVG disablement were less than 15 s because of the optimal characteristics of our IMD.

**IX. Conclusion**

The code-compliant design of electric shock protection in a real PVG has greatly facilitated the application of the standard IEC 60364 in PVGs. The lessons learned through experience produced protective provisions and their adaptation to PVGs. A previous analysis of this standard revealed that: 1) some of the provisions proposed could be directly applied to PVGs without modification since there is no difference between ac LV circuits and dc PV circuits; 2) other provisions needed to be specifically adapted to PV operating characteristics; and 3) others were not applicable.

The creation of an adapted list of guidelines and practices gives PV engineers more freedom when choosing a suitable protection option. Thus, for safety design, protection against electric shock can either be based on “passive” provisions or “passive” as well as “active” provisions with two potential PVG grounding. This flexibility means that such protection can be adapted to the particular conditions of every PVG (e.g., size, accessibility, skill of maintenance teams, importance of economic cost, etc.) and to every country (domestic market and local design practices). Nevertheless, in the context of the requirements analyzed in this paper, each protection option was found to be effective. Furthermore, the elaboration of more codes, guidelines, and standards will doubtlessly foment a wider use of this technology.

This paper presented a theoretical and experimental study of the electrical behavior of a PVG and its electrical shock protection system. It described the theoretical premises necessary to obtain additional protection against direct contact in an ungrounded PVG.

Finally, the feasibility of applying an “active” protective provision was experimentally tested in a real PVG, thus verifying the operating capacity and effectiveness of the hardware available on the market.

**REFERENCES**


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