EARTHING AND LIGHTNING OVERVOLTAGE PROTECTION FOR PV PLANTS

A GUIDELINE REPORT - NOVEMBER 2016

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LEBANESE REPUBLIC
MINISTRY OF ENERGY AND WATER

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Note: The information contained within this document has been developed within a specific scope, and might be updated in the future.

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1.

INTRODUCTION

The Small Decentralized Renewable Energy Power Generation Project, also known as DREG, is funded by the Global Environment Facility (GEF) and implemented through the United Nations Development Programme (UNDP). DREG is executed nationally by the Ministry of Energy and Water (MoEW) in coordination with the Lebanese Center for Energy Conservation (LCEC). The project's objective is to reduce greenhouse gas emissions by the removal of barriers to assist in the distribution and application of decentralized renewable energy power generation.

Part of the project's activities includes focusing on local capacity building. In this regard, DREG organized a workshop in Beirut on *Earthing and Lightning Overvoltage Protections for PV Systems* that was attended by 40 professionals. As a result of the workshop, this guideline came about; it is a working document that principally focuses on PV plants that are embedded in clients' electrical installations. It should be noted that, typically, the DC PV generator will be within the client's premises on a rooftop, façade, or ground mounted.

This guideline does not pretend to be exhaustive; but in the absence of a Lebanese safety code to adhere by, it addresses earthing and overvoltage protection aspects in PV plant design considering the local context. This guideline summarizes some of the relevant international standards, manufacturer's application manuals, and best practices among local electrical engineering practitioners.

This guideline is divided in three main sections; (1) earthing; (2) lightning overvoltage; and (3) other transient overvoltage. In each section, a risk-mitigation procedure has been defined considering the physical and electrical principles behind them, the risks and their causes, and local common practice.

This guideline is complementary to required technical and financial assessments such as energy performance or space availability, interconnection, etc., which are also carried out as part of a feasibility study.

1.1 The Assessment Procedure

This guideline aims at establishing a common and general procedure to ensure safety for persons and equipment in PV plants. Due to the PV market's development characteristics that can be foreseen in Lebanon, it focuses on PV plants that are interconnected to a client's electrical distribution grid. In most cases, these will be rooftop PV plants, but most of the procedures and protection measures suggested also apply to ground-mounted PV plants.

The general procedure consists of a set of three separated procedures, which should be followed by project engineers to ensure that a PV plant is safe for both people and equipment, and plan additional protective measures in case a need is there.

This guideline also highlights the most relevant international standards and some physical principles that explain the causes and risks related to both lightning and earthing.

It contains three procedures, which specifically refer to each one of the three topics covered. These topics are: (1) earthing; (2) lightning overvoltage; and (3) other transient overvoltage.

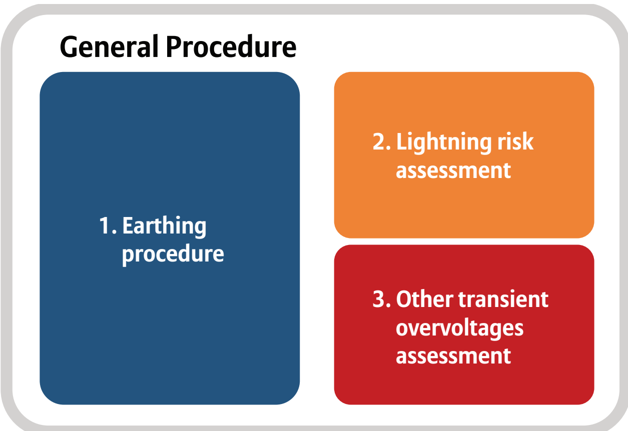


Figure 1 - *General Procedure to assess and select a suitable earthing scheme and lightning overvoltage protection for PV plants*

Each of the steps provides a set of instructions that focus on assessing the current status of the system – either the earthing system or protection against transient overvoltage – and they figure out whether the safety level provided by the system is sufficient, and, once the safety level has been assessed, provide a number of protective measures to be taken in order to ensure the PV plant is safe.

2.

EARTHING

2.1 Earthing Review

■ Why is the earthing system important?

The aim of earthing in electrical installations and circuits is to enhance the safety of the installation by reducing the level of danger inherent to fault currents. Fault currents may be caused by different factors. Therefore, it is very important to design an earthing system according to the installation's characteristics.

■ Purpose of an earthing system:

- Provides safety for persons and animals
- Protects the installation and equipment
- Enhances quality of signal (reduced electromagnetic distortion)
- Provides a fixed reference voltage for equipotentialization

■ Factors to consider at the design stage of an earthing system:

- Soil humidity (reduces earthing resistance)
- Earthing enhancing devices reduce soil resistance
- Buried electricity and gas installations require security distances
- Buried pipes and water tanks shall be bonded equipotentially with earth termination

Fault currents can be transmitted to persons and animals, presenting a high risk through both direct and indirect contact.

2.1.1 Direct Contact

- Direct contacts is defined as an event caused by a person or animal getting in contact with a live conductor of the electrical installation or a normally live conductive element.
- To prevent these events:
  - Insulating cables (with proper insulating materials)
  - Using instantaneous High Sensitivity Residual Current Devices known as HS-RCDs.
- Direct contact protection is independent from the system earthing.

2.1.2. Indirect Contact

- Happens when a person or animal gets into contact with an *exposed-conductive-part.*
- It is the result of an insulation fault that creates a fault current flowing. At the same time, the fault current raises the potential between the devices' frame and the earth, thus causing a fault voltage.
- The fault voltage is considered to be dangerous if it exceeds the Upper Limit voltage.

In order to prevent Direct and Indirect Contacts, the International Electrotechnical Commission (IEC) gave official status to three earthing systems and defined the corresponding installation and protection rules.

IEC 60364 defines three standardized earthing systems schemes:

- Exposed-conductive parts connected to neutral -TN-
- Earthed neutral -TT-
- Unearthed (or impedance-earthed) neutral -IT-

The purpose of all these three earthing systems is the protection of persons and property. They are also considered to ensure safety of persons against indirect contacts.

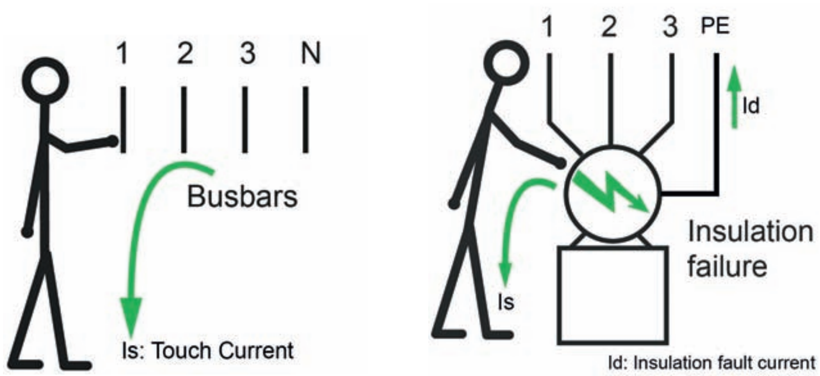


***Figure 2** - Direct (left) and indirect (right) contact representations (Source: Schneider Electric)*

2.1.3 Definitions

National and International Standards provide definitions for a number of devices used in earthing systems. These are:

- **Earth electrode (1):** conductor or group of conductors in intimate contact with, and providing an electrical connection with Earth.
- **Earth:** refers to the conductive mass of the Earth – potential conventionally taken as zero.
- **Electrically independent earth electrodes:** earth electrodes placed at a distance that allows a maximum current flowing through one of them not significantly affecting the potential of the others.
- **Earth electrode resistance:** The electrical resistance of an earth electrode with Earth.
- **Earthing conductor (2):** protective conductor connecting the main earthing terminal (6) of the installation to an earth electrode (1) or to other means of earthing – this will depend on the earthing system used.
- **Exposed-conductive-part:** Conductive part of equipment, which can be touched and which is not a live part, but may become live due to electrical fault events.
- **Main protective conductor (3):** conductor used as protection against electric shocks and intended for connecting together any of the following parts: Exposed-conductive-parts; extraneous-conductive-parts; main earthing terminal; earth electrodes, earthed point of the source or artificial neutral

• **Extraneous-conductive-part (4):** conductive part that may introduce a potential, generally earth potential, and not forming part of the electrical installation (4). For instance:
- Non-insulated floors or walls, metal framework or buildings
- Metal conduits and pipe work for gas, water, etc.

• **Bonding conductor (5):** Protective conductor providing equipotential bonding
• **Main earthing terminal (6):** The terminal or bar connecting protective conductors
• **Removable link (7):** Removable part used to test the earth-electrode-resistance.

Figure 6 provides a visual representation of the definitions mentioned above.

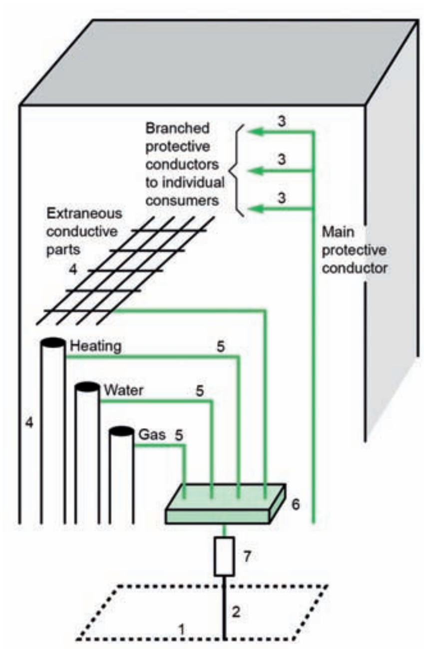


Figure 3 *- Components of an earthing system (Source: Schneider Electric)*

2.1.4 Classification of Components

Most components that can co-exist within an electrical installation are listed and classified below according to the type of element they represent.

Components considered as Exposed-Conductive-Parts	
Component	Example
Aerial cabling	Pipes and conduits
	Impregnated-paper-insulated lead-covered cable
	Mineral insulated metal-sheathed cable
Switchgear	Cradle of withdrawable switchgear
Appliances	Exposed metal parts of Class 1 insulated appliances
Non-electrical elements	Metallic fittings associated with cableways
	Metal objects (close to aerial conductors or to bus bars)
	Metal objects (in contact with electrical equipment)

Table I *- Components of an electrical installation considered as Exposed-Conductive-Parts (Source: Schneider Electric)*

Components NOT considered as Exposed-Conductive-Parts	
Component	Example
Diverse service channels, ducts	Conduits made of insulating material
	Moldings in wood or other insulating material
	Conductors and cables without metallic sheaths

Table II - *Components of an electrical installation not considered as Exposed-Conductive-Parts (Source: Schneider Electric)*

Components considered as Extraneous-Conductive-Parts	
Component	Example
Elements used in building construction	Metal or reinforced concrete
	Surface finishes
	Metallic covering
Building services elements other than electrical	Metal pipes
	Conduits
	Related metal components
	Metallic fittings in wash rooms, bathrooms, others
	Metalized papers

Table III - *Components of an electrical installation considered as Extraneous-Conductive-Parts (Source: Schneider Electric)*

Components NOT considered as Extraneous-Conductive-Parts
Component/Example
Wooden-block floors
Rubber-covered or linoleum-covered floors
Dry plaster-block partition
Brick walls
Carpets and Wall-to-Wall carpeting

Table IV - *Components of an electrical installation not considered as Extraneous-Conductive-Parts (Source: Schneider Electric)*

2.1.5 Types of Connections

Main Equipotential Bonding

- It aims to ensure that no difference of potential can occur between *Extraneous-Conductive-Parts* in the event of an incoming extraneous conductor raised to its potential due to an external fault in the installation or building. No difference of potential can occur between extraneous-conductive-parts within the installation.

- The bonding connection must be as close as possible to the entrance of the building and it must be connected to the main earthing terminal.

- Regarding metallic sheaths of communication cables, an authorization from the owner is required.

Supplementary Equipotential Connections

- Serves as a higher level of safety by connecting all exposed- and extraneous-conductive-parts that can be touched simultaneously, creating a more robust equipotentially-bonded system.
- Especially important when original bonding conductors present high electrical resistance.

Connection of Exposed-conductive-parts to the Earth Electrode

- Aims at providing a low-electrical resistance path for fault currents flowing to earth.

2.1.6 Types of Earth Electrode Installation Methods

Buried ring

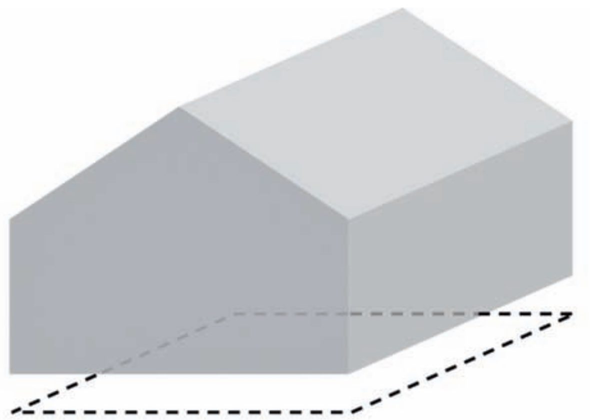


Figure 4 **-** *Buried ring earthing (Source: Schneider Electric)*

- Strongly recommended (specially for new buildings)
- Earth electrode buried around the perimeter of the foundations
- The earth conductor must be in direct contact with the soil
- At least four separated vertical conductors from the electrode should be installed and, if possible, reinforcing rods should be connected to the electrode
- For existing buildings, the electrode conductor should be buried around the outside wall at least, one meter of depth
- Conductors may be:
  - Copper: bare cable (≥25 mm2) or multiple-strip (≥25 mm2 and ≥2 mm)
  - Aluminum with lead jacket (≥35 mm^2)
  - Galvanized-steel cable (≥95 mm^2) or multiple-strip (≥100 mm^2 and ≥3 mm thick)

- **Resistance calculation:** R= 2×ρL ;

where L:length of conductor m and ρ:resistivity of the soil

Earthing Rods

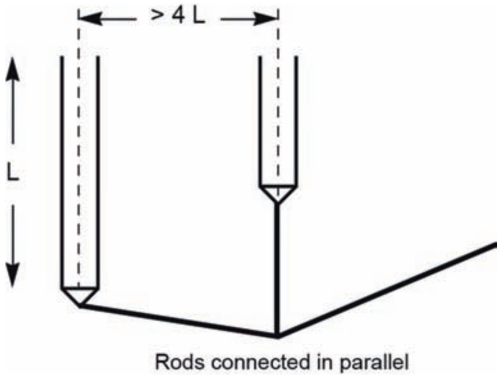


Figure 5 - *Earth rods connected in parallel (Source: Schneider Electric)*

- Often used for existing facilities, and also used to improve existing earth electrodes
- Rods may be:
  - Copper or copper-clad steel (one or two meters long, and screwed ends and sockets)
  - Galvanized steel pipe (≥25 mm diameter) or rod (≥15 mm diameter) in both cases ≥2 meters long
- Distance between rods should be two or three times depth
- **Resistance calculation for n rods:** $R = \rho n \times L$

Vertical Plates

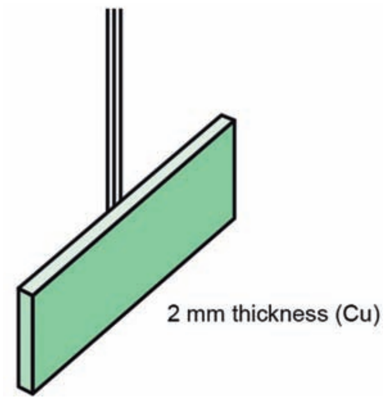


Figure 6 - *Vertical plate (Source: Schneider Electric)*

- Rectangular plates of at least 0.5 meters used as earth electrodes
- Buried in a vertical plane to a depth where the center of the plates is at least one meter below the surface
- Plates may be:
  - Copper (2 mm thickness)
  - Galvanized steel of 3 mm thickness

- **Resistance calculation for n rods:** $R = 0.8 \times \rho\ L$

2.1.7 Earth Resistance Measurement

To estimate the resistance to earth, you can use the formulas given above for calculating the resistance for each kind of installation method (buried ring, vertical plates, or/and rods).

- Buried ring: $R = 2 \times \rho L$
- Earthing rods (for n rods): $R = \rho n \times L$
- Vertical plates: $R = 0.8 \times \rho L$
- Resistance to earth can also be measured empirically using an ammeter.
  - The installation should have removable links that allow the earth electrode to be isolated from the installation; so periodic tests can be carried out (Figure 7).

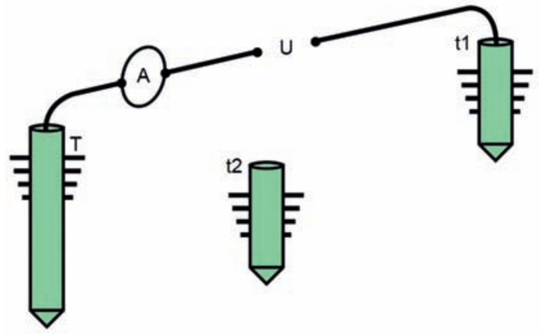


Figure 7 - *Measurement of the resistance to earth of the earth electrode of an installation by means of an ammeter (Source: Schneider Electric)*

Influence of Type of Soil on Resistivity

Influence of Type of Soil on Resistivity	
Type of Soil	Mean Value of Resistivity in Ωm
Swampy soil, bogs	1 – 30
Silt alluvium	20 – 100
Humus, leaf mould	10 – 150
Peat, turf	5 – 100
Soft clay	50
Marl and compacted clay	100 – 200
Jurassic marl	30 – 40
Clayey sand	200 – 300
Siliceous sand	200 – 300
Stoney ground	1500 – 3000
Grass-covered-stoney sub-soil	300 – 500
Chalky soil	100 – 300
Limestone	1000 – 5000
Fissured limestone	500 – 1000
Schist, shale	50 – 300
Mica schist	800
Granite and sandstone	1500 – 10000
Modified granite and sandstone	100 – 600

Table V - *Resistivity ranges per type of soil*

2.1.8 Standardized Earthing Schemes

The selection of protective measures against indirect current will depend on the earthing distribution scheme. Three independent possibilities:

- The type of connection of the electrical system and the type of the exposed parts to earth (typically neutral conductor).
- Additionally include either a separate protective conductor or the protective conductor and the neutral conductor can be a single conductor.
- To use earth fault protection of overcurrent protective switchgear (this protection clears only at relatively high fault currents) or to use additional relays that are able to detect and to clear small insulation fault currents to earth.

All three choices are standardized as earthing system schemes.

Advantages and drawbacks coming with the selected choice:

- Connection of exposed-conductive-parts and neutral conductor to the Potential Earth (PE) conductor:
  - Pro: Results in equipotentiality and lower overvoltage
  - Con: Increases earth fault current
- Separate protective conductor (SPC) vs. Neutral conductor
  - Pros: (with SPC) Much more unlikely to be polluted by voltage drops and harmonics. Leakage currents are also avoided
  - Cons: Costly, even if it has a small cross-sectional area
- Residual current protective relays against insulation monitoring devices
  - Pros: (with RCPR) Much more sensitive and typically permits clearing faults before heavy damage occurs.
  - Cons: (with RCPR) Independent of changes in an existing installation

TT Systems

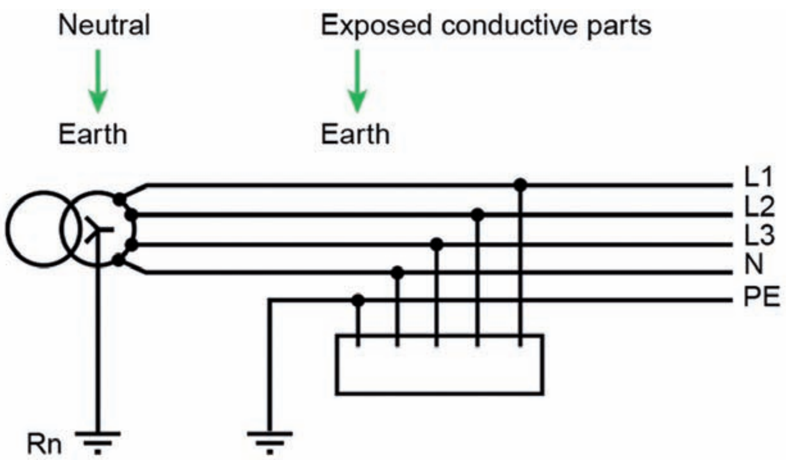


Figure 8 - TT System (Source: Schneider Electric)

General Information

- One point at the supply source is directly earthed
- Exposed- and extraneous-conductive-parts are connected to a separate earth electrode which can or cannot be electrically independent

Characteristics

- Simplest solution to design and install
- Does not require continuous monitoring during operation
- Protection ensured by special devices (Residual Current Devices)
- Insulation faults result in interruption of power supply
- Loads or parts of the installation causing high leakage currents during operation require special measures to avoid nuisance tripping (i.e. supply the loads with a separation transformer or use specific RCDs)

TN Systems (earthed neutral)

General Information

- Supply source directly earthed (as for the TT)
- Exposed- and extraneous-conductive-parts are connected to the neutral conductor

Characteristics

- Requires earth electrodes at regular intervals
- Requires initial check on effective tripping for the first insulation fault
- Insulation faults may result in greater damage to rotating machines
- Higher risk of fire

TN Systems Configurations

- TN-C System

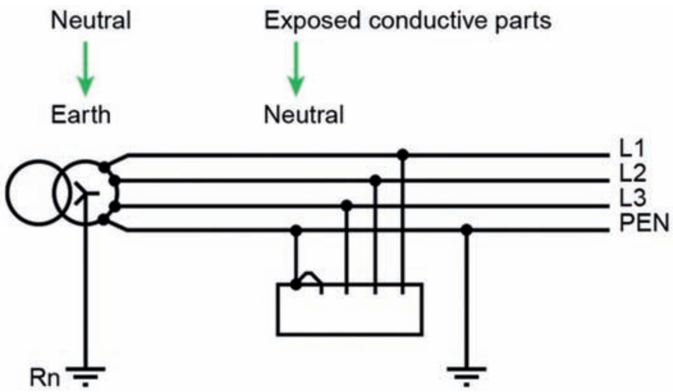


***Figure 9** - TN-C System (Source: Schneider Electric)*

- eutral conductor used as a protective conductor (Protective Earth and Neutral Conductor)
- Conductors must be larger than 10 mm^2
- Requires an effective equipotential environment with dispersed earth electrodes spaced as regularly as possible
- PEN conductor must be connected to a number of earth electrodes in the installation
- Appear to be cheaper (due to use of one less pole and conductor)
- Requires fixed and rigid conductors
- Forbidden for:
  - Premises with fire risk
  - For computer equipment due to presence of harmonic currents in the neutral conductor

■ TN-S System

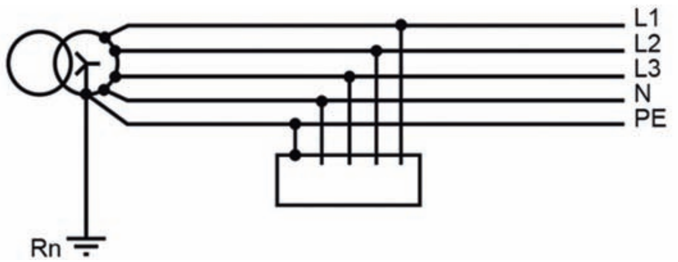


Figure 10 *- TN-S System (Source: Schneider Electric)*

- Configuration consisting of five wires
- Mandatory for circuits with cross-sectional areas below 10 mm^2 for portable equipment
- Protective and neutral conductors are separate
- May be used even with flexible conductors and small conduits
- Provides a clean PE (ideal for computer systems)

a. TN-C-S System

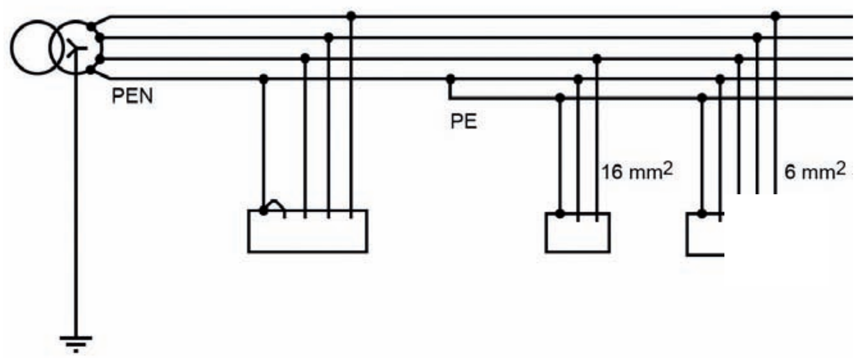


Figure 11 *- TN-C-S System (Source: Schneider Electric)*

- Combination of TN-C and TN-S system
- TN-C system (4 wires) must never be installed downstream the TN-S system (five wires) due to security reasons

■ IT Systems

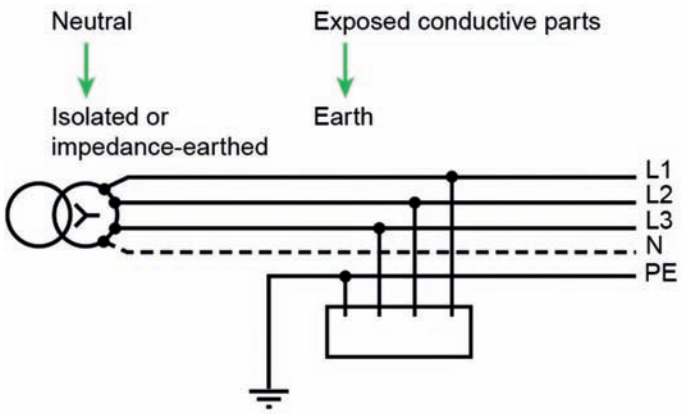


Figure 12 *- IT System (Source: Schneider Electric)*

General Information

- Neutral point of the source is not connected to earth
- Exposed- and extraneous-conductive-parts are connected to earth

Characteristics

- Best continuity of service during operation
- Indication of first insulation fault (this ensures systematic prevention of outages)
- Requires periodic maintenance
- Requires high level of insulation network
- Protection of the neutral conductor must be ensured by:
  - Isolated ground
  - Neutral with earth impedance connection

Important

It is important to take into account that the selection of the earthing system scheme (TT, TN, IT) **does not depend on safety criteria** since the three standardized earthing systems schemes are equivalent in terms of protection to persons.

Thus, selection criteria depend on:

- Regulatory requirements
- Required continuity of service
- Operating conditions

Table V and table VI classify and characterize different earthing connection schemes.

	TT	TN-S	TN-C	IT1[(a)]	IT2[(b)]	Comments
Electrical characteristics						
Fault current	-	- -	- -	+	- -	Only the IT system offers virtually negligible first-fault currents
Fault voltage	-	-	-	+	-	In the IT system, the touch voltage is very low for the first fault, but is considerable for the second
Touch voltage	+/- -	-	-	+	-	In the TT system, the touch voltage is very low if system is equipotential, otherwise it is high
Protection						
Protection of persons against indirect contact	+	+	+	+	+	All SEAs (system earthing arrangement) are equivalent, if the rules are followed
Protection of persons with emergency generating sets	+	-	-	+	-	Systems where protection is ensured by RCDs are not sensitive to a change in the internal impedance of the source
Protection against fire (with an RCD)	+	+	Not allowed	+	+	All SEAs in which RCDs can be used are equivalent. The TN-C system is forbidden on premises where there is a risk of fire
Overvoltages						
Continuous overvoltage	+	+	+	-	+	A phase-to-earth overvoltage is continuous in the IT system if there is a first insulation fault
Transient overvoltage	+	-	-	+	-	Systems with high fault currents may cause transient overvoltages
Overvoltage if transformer breakdown (primary/secondary)	-	+	+	+	+	In the TT system, there is a voltage imbalance between the different earth electrodes. The other systems are interconnected to a single earth electrode
Electromagnetic compatibility						
Immunity to nearby lightning strikes	-	+	+	+	+	In the TT system, there may be voltage imbalances between the earth electrodes. In the TT system, there is a significant current loop between the two separate earth electrodes
Immunity to lightning strikes on MV lines	-	-	-	-	-	All SEAs are equivalent when a MV line takes a direct lightning strike
Continuous emission of an electromagnetic field	+	+	-	+	+	Connection of the PEN to the metal structures of the building is conducive to the continuous generation of electromagnetic fields
Transient non-equipotentiality of the PE	+	-	-	+	-	The PE is no longer equipotential if there is a high fault current
Continuity of service						
Interruption for first fault	-	-	-	+	+	Only the IT system avoids tripping for the first insulation fault
Voltage dip during insulation fault	+	-	-	+	-	The TN-S, TNC and IT (2nd fault) systems generate high fault currents which may cause phase voltage dips
Installation						
Special devices	-	+	+	-	-	The TT system requires the use of RCDs. The IT system requires the use of IMDs
Number of earth electrodes	-	+	+	-/+	-/+	The TT system requires two distinct earth electrodes. The IT system offers a choice between one or two earth electrodes
Number of cables	-	-	+	-	-	Only the TN-C system offers, in certain cases, a reduction in the number of cables
Maintenance						
Cost of repairs	-	- -	- -	-	- -	The cost of repairs depends on the damage caused by the amplitude of the fault currents
Installation damage	+	-	-	++	-	Systems causing high fault currents require a check on the installation after clearing the fault

(a) IT-net when a first fault occurs.
(b) IT-net when a second fault occurs.

Table VI - *Comparison of system earthing arrangements (Source: Schneider Electric)*

Type of network	Advised	Possible	Not advised
Very large network with high-quality earth electrodes for exposed conductive parts (10 Ω max.)		TT, TN, IT (1) or mixed	
Very large network with low-quality earth electrodes for exposed conductive parts (> 30 Ω)	TN	TN-S	IT (1) TN-C
Disturbed area (storms) (e.g. television or radio transmitter)	TN	TT	IT (2)
Network with high leakage currents (> 500 mA)	TN (4)	IT (4) TT (3) (4)	
Network with outdoor overhead lines	TT (5)	TN (5) (6)	IT (6)
Emergency standby generator set	IT	TT	TN (7)
Type of loads			
Loads sensitive to high fault currents (motors, etc.)	IT	TT	TN (8)
Loads with a low insulation level (electric furnaces, welding machines, heating elements, immersion heaters, equipment in large kitchens)	TN (9)	TT (9)	IT
Numerous phase-neutral single-phase loads (mobile, semi-fixed, portable)	TT (10) TN-S		IT (10) TN-C (10)
Loads with sizeable risks (hoists, conveyers, etc.)	TN (11)	TT (11)	IT (11)
Numerous auxiliaries (machine tools)	TN-S	TN-C IT (12 bis)	TT (12)
Miscellaneous			
Supply via star-star connected power transformer (13)	TT	IT without neutral	IT (13) with neutral
Premises with risk of fire	IT (15)	TN-S (15) TT (15)	TN-C (14)
Increase in power level of LV utility subscription, requiring a private substation	TT (16)		
Installation with frequent modifications	TT (17)		TN (18) IT (18)
Installation where the continuity of earth circuits is uncertain (work sites, old installations)	TT (19)	TN-S	TN-C IT (19)
Electronic equipment (computers, PLCs)	TN-S	TT	TN-C
Machine control-monitoring network, PLC sensors and actuators	IT (20)	TN-S, TT	

(1) When the SEA is not imposed by regulations, it is selected according to the level of operating characteristics (continuity of service that is mandatory for safety reasons or desired to enhance productivity, etc.)
Whatever the SEA, the probability of an insulation failure increases with the length of the network. It may be a good idea to break up the network, which facilitates fault location and makes it possible to implement the system advised above for each type of application.
(2) The risk of flashover on the surge limiter turns the isolated neutral into an earthed neutral. These risks are high for regions with frequent thunder storms or installations supplied by overhead lines. If the IT system is selected to ensure a higher level of continuity of service, the system designer must precisely calculate the tripping conditions for a second fault.
(3) Risk of RCD nuisance tripping.
(4) Whatever the SEA, the ideal solution is to isolate the disturbing section if it can be easily identified.
(5) Risks of phase-to-earth faults affecting equipotentiality.
(6) Insulation is uncertain due to humidity and conducting dust.
(7) The TN system is not advised due to the risk of damage to the generator in the case of an internal fault. What is more, when generator sets supply safety equipment, the system must not trip for the first fault.
(8) The phase-to-earth current may be several times higher than In, with the risk of damaging or accelerating the ageing of motor windings, or of destroying magnetic circuits.
(9) To combine continuity of service and safety, it is necessary and highly advised, whatever the SEA, to separate these loads from the rest of the installation (transformers with local neutral connection).
(10) When load equipment quality is not a design priority, there is a risk that the insulation resistance will fall rapidly. The TT system with RCDs is the best means to avoid problems.
(11) The mobility of this type of load causes frequent faults (sliding contact for bonding of exposed conductive parts) that must be countered. Whatever the SEA, it is advised to supply these circuits using transformers with a local neutral connection.
(12) Requires the use of transformers with a local TN system to avoid operating risks and nuisance tripping at the first fault (TT) or a double fault (IT).
(12 bis) With a double break in the control circuit.
(13) Excessive limitation of the phase-to-neutral current due to the high value of the zero-phase impedance (at least 4 to 5 times the direct impedance). This system must be replaced by a star-delta arrangement.
(14) The high fault currents make the TN system dangerous. The TN-C system is forbidden.
(15) Whatever the system, the RCD must be set to $\Delta n \leq 500$ mA.
(16) An installation supplied with LV energy must use the TT system. Maintaining this SEA means the least amount of modifications on the existing network (no cables to be run, no protection devices to be modified).
(17) Possible without highly competent maintenance personnel.
(18) This type of installation requires particular attention in maintaining safety. The absence of preventive measures in the TN system means highly qualified personnel are required to ensure safety over time.
(19) The risks of breaks in conductors (supply, protection) may cause the loss of equipotentiality for exposed conductive parts. A TT system or a TN-S system with 30 mA RCDs is advised and is often mandatory. The IT system may be used in very specific cases.
(20) This solution avoids nuisance tripping for unexpected earth leakage.

Table VII – Influence of networks and loads on the selection of system earthing arrangement (Schneider Electric)

2.2 Earthing System Assessment Procedure

Most PV plants for self-generation will be embedded into the existing electrical installations in the client's facilities. In Lebanon, many existing buildings have poor earthing systems or even none at all. Therefore, when assessing a potential site for a PV plant, one shall assess and advise the client whether it is necessary to upgrade or install a new earthing system for the PV plant's safety and also for the client's existing electrical installation. The earthing assessment process involves the following steps:

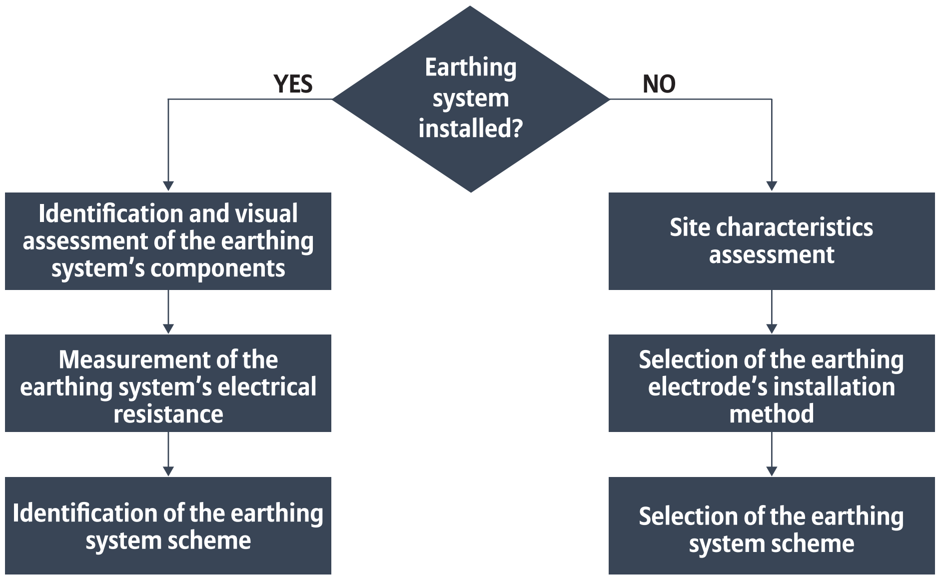


Figure 13 - *Steps of the earthing assessment procedure*

Based on the above figure, two possible scenarios are considered in this guide:
a) When there is an earthing system installed
b) When there is not an earthing system installed

2.2.1 Steps of the Earthing Assessment Procedure

Case A Earthing system installed:

If an earthing system is already installed at the site, it should be assessed to identify whether the quality of this earthing is sufficient for the PV plant. If the earthing system meets the requirements, no action will be necessary. In case the earthing does not meet the technical requirements, it should be enhanced in order to ensure the required level of safety. The steps for this procedure are:

Step 1: Identification and visual assessment of earthing system components

Guide references:
- 2.1.3 Definitions
- 2.1.4 Classification of components
- 2.1.5 Types of connections
- 2.1.6 Types of earth electrode installation method

How?

Visual inspection of the electrical installation and electrical drawings if available.

Result

Identification of: main protective conductor, exposed- and extraneous-conductive-parts, bonding conductor, and earth electrode(s) and connections.

Comments

Once identified, a visual inspection and/or assessment of these components should be carried out in order to make sure the installation fits to the current earthing system.

Step 2: Measurement of the earthing system's electrical resistance and continuity

Guide references:

2.1.7 Earth resistance measurement

How?

- Check continuity between the main earthing network and the earth bar to which the PV plant will be connected.
- Measurement of the electrical resistance to earth by means of an ammeter (Ammeter Method)

Result

Value of the earthing system's electrical resistance to earth

Comments

- Depending on the value of the electrical resistance, the following actions are recommended:
  If $R < 5$ ohms: good quality earthing system, and therefore, can be used for the PV plant.
  If $5 < R < 60$[1] ohms: it can be used but with caution. In this case it is recommended to enhance the quality of the earthing system if possible.
  If $R > 60$ ohms: The earthing resistance is too high. The quality of the earthing system shall be improved.
- In order to improve the earthing system, additional rods and/or plates can be installed.

Step 3: Identification of the earthing system scheme

Guide references:

2.1.8 Standardized Earthing Schemes

How?

Visual inspection of the electrical installation and electrical drawings if available.

Result

Type of earthing system scheme

Comments

It is recommended that the responsible party for the earthing system installation should analyze and inform the client about the type of earthing system scheme installed. It might be good to review it according to the type of loads, electricity service requirements, risks inherent to the installation, and local common practice.

1- There is not a maximum value for the earth resistance set by standards. International best practices from the PV sector and corroborated by several experienced PV designers, an earthing resistance of up to 60 could be used. However, if there is sensitive equipment it may be relevant to consider a lower value if possible.

Case B Earthing system NOT installed:

If an earthing system is not installed at the site, the client should be informed and an earthing system should be installed to meet the requirements of the PV plant. In order to select the best earthing system components, scheme, and installation method, the following steps are recommended:

Step 1: Site characteristics assessment

Guide references:
- 2.1.3 Definitions
- 2.1.6 Types of earth electrode installation method

How?
- The site where the earthing system should be assessed according to the following criteria:
  - Type of soil
  - Type of appliances and loads
  - Identification of extraneous- and exposed-conductive parts Identification of equipotential bonding conductors

Result

Model of the installation site's characteristics

Comments

The results of the assessment of proposed criteria will later be used during the design of the type and sizing of the earthing electrode's installation method

Step 2: Selection of the earthing electrode's installation method

Guide references:
- Classification of components
- 2.1.5 Types of connections
- 2.1.6 Types of earth electrode installation method

How?

The type of installation method of the earth electrode (buried ring, vertical plates and/or rods) will be selected according to the characteristics described previously in this guide, and also, according to the results of the previous step (Step 1).

Result

Selected earth electrode installation method

Comments
- Despite the buried ring installation method, which is highly recommended, it may not always be possible. Consequently, all installation methods should be considered.
- During the design stage, the resistance of the installation method can be estimated by calculating it with the provided formulas.

Step 3:
Selection of the earthing system scheme

Guide references:
- 2.1.7 Earth resistance measurement
- 2.1.8 Standardized Earthing Schemes

How?

The earthing system scheme will be selected according to the load and appliances characteristics, to the service requirements and risks, and local common practice. It is recommended to do this selection after consulting the client.

Result

Selected earthing system scheme

Comments

Once the earthing system is installed, it is recommended to measure theresistance to earth to ensure the quality of it.

Other factors influencing the resistance to earth:
- Humidity of the soil: Seasonal changes in the moisture content can be significant at depths of up to two meters.
- Frost: Frozen earth increases resistivity of the soil.
- Ageing: The materials used for electrodes deteriorate due to chemical reactions and other types of reactions.
- Oxidation: Brazed and welded joints and connections are the most sensitive points to oxidation.

2.3 Earthing at PV Plants

- Involves exposed conductive parts and the live parts of the generation power system.
- Exposed conductive parts include metal frame of the PV modules and other parts of the power plant that, even though should be isolated, could have current circulating through them by a fault event (e.g. metal racks and structures). The generation power system refers to live parts of the PV plant.
- It is important to differentiate between the AC side and the DC side. Two different cases:
  - PV plants with galvanic insulation of the DC side from the electrical grid can be functionally earthed
  - PV plants without galvanic isolation of the DC side from the grid cannot be functionally earthed.

Plants with Galvanic Isolation

- The PV generator can either be insulated or earthed as protection against indirect contacts.
- Important to differentiate between exposed conductive parts upstream and downstream the galvanic isolation point of the installation.

Exposed Parts on the PV side of the Galvanic Isolation

- **At plants with an isolated PV generator**, live parts are insulated from earth while the exposed conductive parts are earthed:

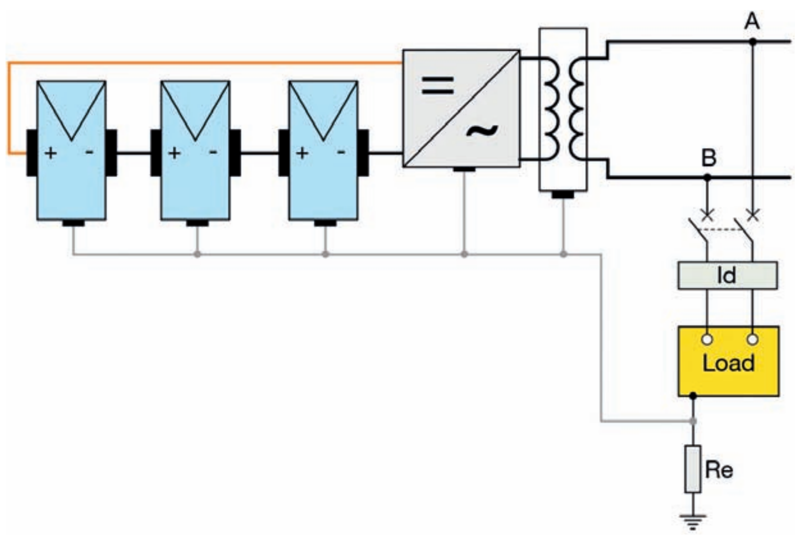


Figure 14 - *Plant with isolated PV generator*

- The earthing system of a PV plant is common with the site's earthing system. Frames and supporting structures of the PV generator must be earthed as well.

- Recommendation: the earthing resistance (**Re** of the exposed conductive parts meets the condition) (According to IEC 60364-6): Re ≤ 120Id
  - **Id**: current of first fault to earth. Typically, very low in small-sized plants. In the case of double faults, the voltage of interconnected exposed conductive parts will be lower than (According to IEC 60364-6):
    - Isc*Reqp ≤120V
  - **Isc**: short-circuit current of the PV modules involved.
  - **Reqp**: Resistance of the conductor interconnecting exposed conductive parts affected.
- **In larger plants**, the second fault can cause very harmful problems.
  Usually an insulation surveillance controller is installed (often integrated inside the power conversion unit).
  In NEC2011 (National Electrical Code, USA) there's a specific regulation that mandates to install AFCI (arc fault circuit interrupters) to avoid further problems (fire, explosions, etc.) after a series arc fault.

- **Plant with a functionally earthed PV generator**: live parts and exposed conductive parts are connected to the same earthing system (the site's earthing).

  - If there is an earth fault, short-circuit happens, but the current cannot be detected by maximum current devices since the PV plants' fault currents are not much higher than the rated current. Due to this difference between PV plants' fault currents and the rated current, large PV plants operating at a low voltage (LV <1 000 V) will become high risk plants. This risk is limited in the case of smaller plants or when PV generators do not exceed extra low voltage ELV (<75 V DC).

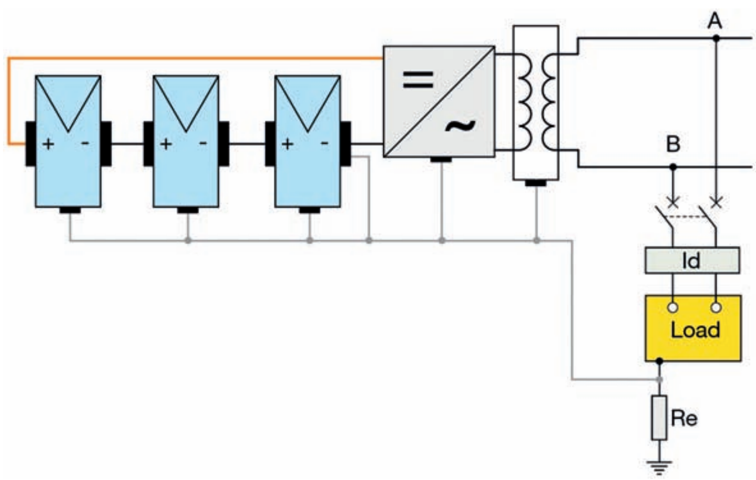


Figure 15 *- PV plant with a functionally earthed system*

Exposed Parts Downstream the Galvanic Isolation

- **Plant with functional earthed PV generator:** exposed conductive parts protected by a residual current circuit-breaker installed at the beginning of the site's electrical installation are protected towards the grid as well as towards the PV generator.

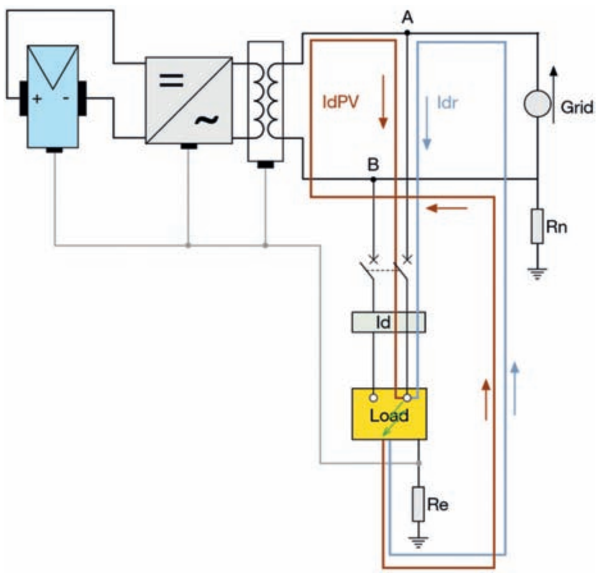


Figure 16 *- Exposed conductive parts in a plant with Isolated PV generator on the AC side of the transformer*

- It is important that exposed conductive parts are not placed upstream of the residual current circuit breakers (between the RCCB and the grid connection point).

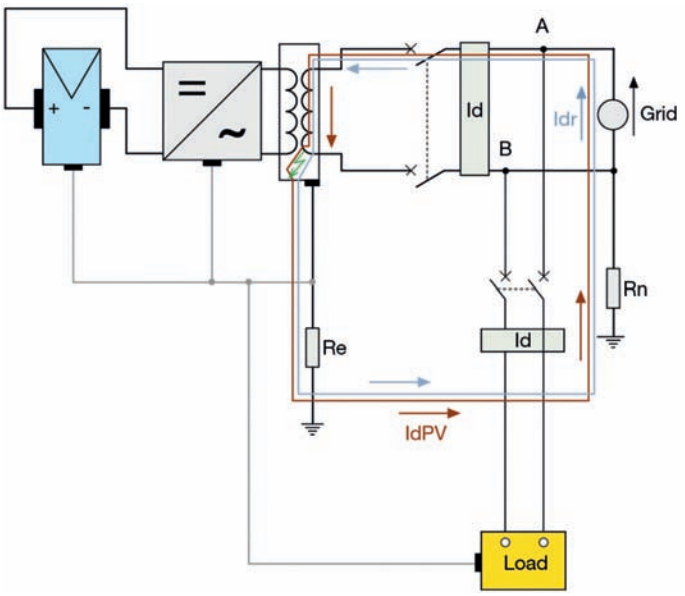


Figure 17 *- Current fault example in a floating PV Plant*

- A residual current protection device should specifically be installed to protect exposed conductive parts between the transformer's secondary and the circuit breakers.

2.3.1 Plants without galvanic isolation

- Live parts of the PV installation must be insulated from earth.

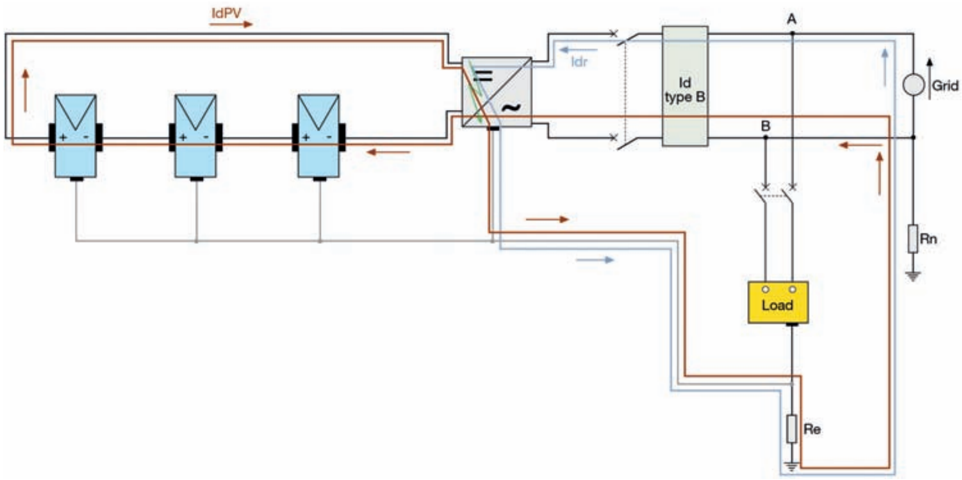


***Figure 18** - Current fault example at a plant without galvanic isolation*

- *On the DC side*

  - Fault on the exposed conductive parts causes tripping of the residual current circuit-breaker positioned on the AC side of the power conversion unit, or tripped/flagged by a residual current monitoring unit (RCMU) integrated in the power conversation unit.
  - Once the protection trips, the power conversion unit shifts to standby due to the lack of grid voltage at its output.
  - Even though the power conversion unit shifts to standby or stops, live parts of the DC side are still energized from solar radiation.

- *On the AC side*

  - If there is a fault on the DC side, residual current circuit-breakers on the AC side of the power conversion unit should be of type B (so they trip with direct current) unless the power conversion unit is by construction cutting the injection of DC earth fault currents (IEC 60364-7).

NOTE

In North America, earthing is theoretically done on all PV plants above 25 V, whether AC or DC. The difference between North American systems and others is that one of the *current-carrying* conductors (the *neutral conductor*) is intentionally grounded. The principle is that when a flaw occurs, it will complete the circuit through the ground. The faulted circuit will keep equipment that is not intended to carry current de-energized, therefore, safer to service a system that is known to have a problem. However, this type of system is extremely hazardous to touch under normal operating conditions.
Conversely, with floating (ungrounded) systems the opposite is true: a normally operating circuit can be contacted without hazard, but a faulted circuit can energize non-current-carrying equipment, making it more hazardous to service.

2.4 Review of Relevant Standards

Relevant regulation for earthing at PV plants is described in IEC 60364-7-712 – Low-voltage electrical installations – Part 7-712: Requirements for special installations or location – Solar photovoltaic (PV) power supply installations.

2.4.1 Functional Earthing

Functional earthing refers to the connection of one live part of the PV module/generator to earth. Most PV module technologies do not require functional earthing to operate. However, some PV module technologies require a live polarity to be connected to earth for functional reasons.

- According to IEC 60364, functional earthing of live parts on the DC side of power conversion equipment is permitted as long as there is galvanic separation between the primary and secondary (DC and AC) side.
- The functional earthing shall be located at a single point of the DC side, as close as possible to the power conversion unit, between the disconnection device and the DC terminals of the power conversion unit.
- When DC earthing is direct, in order to avoid overcurrent upstream of the earthing, automatic disconnection is required to eliminate any fault current flowing in the functional earthing conductor.
- When DC earthing is via resistor, an Insulation Monitoring Device (IMD) shall be installed.

2.4.2 Safety Issues

The maximum operating voltage in the nameplate of the PV modules should always be checked. In general, PV generators for installation shall not have a maximum voltage greater than 1,000 V DC. The entire PV generator and associated wiring and protection shall have restricted access to competent persons only and shall be labeled with warning and danger signs.

- Regarding protection against the effects of insulation faults, PV generators are categorized as: *Non Separated PV generators*[2] (e.g. PV generator connected to an earth referenced system through a non-separated Power Conversion Equipment (PCE).)
- *Functionally earth PV generators* (e.g. a PV generator with one of the main conductors connected to a functional earth.)
- *Non-earth referenced PV generators* (e.g. a PV generator that has none of its main conductors referenced to earth.)

2- Functionally earthed systems include PV generators connected via a protection/isolation device to the system earth or connected via a resistance to the system earth.

PV plant type				
		Non Separated PV	Functionally earthed PV	Isolated PV
PV Generator Earth Insulation Resistance	Measurement	This can be done either by an insulation measuring device or by an insulation monitoring device. It should measure the installation resistance immediately before commissioning and at least once every 24 hours.		
	Action on fault	Shut down PCE and disconnect all the PV generator's AC poles from the PCE or disconnect all the faulty portion's poles of the generator from the PCE (operation is allowed)	Shut down PCE and disconnect all the faulty portion's poles of the PV generator from earth (operation is allowed)	Connection to the AC circuit is allowed (PCE is allowed to operate)
	Indication on fault		Indicate a fault in accordance. If the generator insulation resistance has recovered to a value higher than the limit shown in Table 2, the circuit is allowed to reconnect	
PV Earth Fault Detection by means of current monitoring	Detection / protection	Detection by a residual current monitoring system (AC and DC side)	Residual current monitoring system or a device or association of devices, in accordance with IEC 62548	
	Action on fault	Shut down PCE and disconnect all conductors of the AC circuit or all the PV generator's poles from the PCE or disconnect all of the faulty portion's poles of the PV generator from the PCE (operation is allowed)	Disconnect all of the faulty portion's poles of the PV generator from the PCE or functional earth connection shall be disconnected. Connection to the AC circuit is allowed (PCE allowed to operate)	
	Indication on fault	The indication shall be of a form that ensures the system operator or owner of the system becomes aware of the fault (visible audible, or via email, SMS, or similar) The indication shall be of a form that ensures the system operator or owner of the system becomes aware of the fault (visible audible, or via email, SMS, or similar)	Disconnect all of the faulty portion's poles of the PV generator from the PCE or functional earth connection shall be disconnected. Connection to the AC circuit is allowed (PCE allowed to operate)	

Table VIII *- Requirements for different system types based on type of power conversion equipment's isolation and PV generator functional earthing (Source: IEC 62548)*

2.4.3 Functionally Earthed

When required by Table IX and residual current monitoring is not provided, a functionally earthed PV generator shall be installed with an earth fault-interrupting device.

- Interrupting device is NOT required as long as:
  - The PV generator is functionally earthed
  - The resistance is sufficiently high (according to the table below) so that maximum current through the generator-functional earth path due to single faults is less than the limits set in the table below.

Total PV Generator Power rating (kWp)	Rated Current In (A)
0 – 25	1
>25 – 50	2
>50 – 100	3
>100 – 250	4
>250	5

***Table IX** - Rated current requirements for not installing an automatic disconnecting device (Source: IEC 62548)*

Requirements for Protections Against Overcurrent.

Overcurrent protective devices required to protect the PV modules and their wiring shall be selected to reliably and consistently operate within two hours when an overcurrent of 135% of the nominal device current rating of the PV modules is applied.

3.

LIGHTNING OVERVOLTAGE

3.1 Review

Lightning events are one of the threats to electrical installations due to the many atmospheric discharges during a lightning storm. These discharges can reach up to hundreds of kiloamperes.

Lightning does not only represent a hazard to the electrical installation but also to people, animals, buildings, and electronic equipment. The negative economic consequences of lightning can be very high. Currently, despite technological advances, no device is able to prevent lightning formation. However, Lightning Protection Systems (LPS) are able to minimize damage to the surrounding environment. Damage to electrical installations can come from a direct strike or from induced overvoltage (indirect strike).

3.1.1 Characterization of the Lightning Wave

Lightning protection theory assumes lightning creates a direct discharge wave, a double exponential whose rise time is 10 µs, with a peak value of 100 kA, and a tail time of 350 µs.

- 10/350 µs wave: direct lightning strike

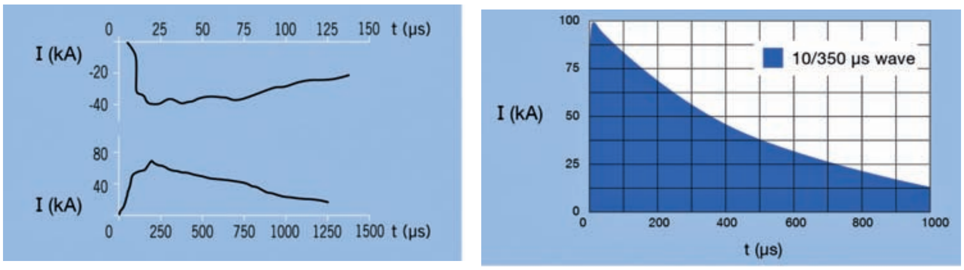


Figure 19 - Wave shape and intensities of positive (ground to cloud) and negative (cloud to ground) discharges (left). The measured values for intensity of lightning peak current range from hundreds of amperes to several hundred of kiloamperes (right).

- Two models determined to classify overvoltage:
  Direct overvoltage → From direct strike
  Indirect/Induced overvoltage → From indirect strike

- Direct wave model – 10/350 µs wave

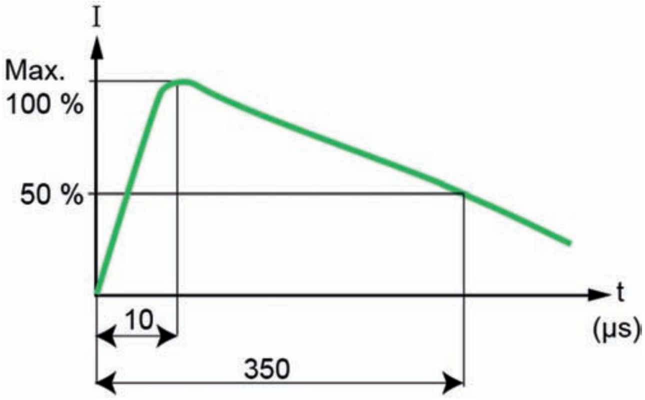


Figure 20 - Direct strike wave model

It takes 10 µs for the wave to reach 100% of the maximum value
The second number is the tail time. The tail time is the time it takes to reach 50% of the value after the wave has reached 100%.
Direct lightning tail time: 350 µs

- Indirect wave model – 8/20 µs

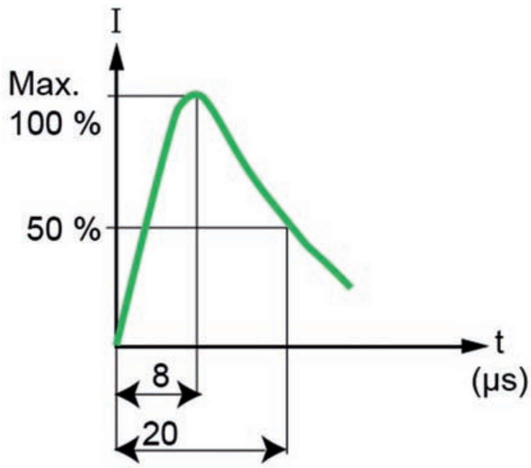


Figure 21 - Indirect strike wave model

Indirect lightning wave has a rise up time of 8 µs and a tail time of 20 µs.

3.1.2 Transient Overvoltage

- Definition: Very short voltage increases between two conductors or between one conductor and the ground.

]■ Transient overvoltage may enter an electrical installation via the electrical power supply, telephone, TV or data lines, or even through the earthing which then transmits it to the connected equipment.

■ Most typical causes of transient overvoltage are:
Switching operations of machinery
Grid failure event
Indirect lightning strikes

■ Consequences range from simple disruptions (interruption of operations or computer failures) to the total heavy damage to main components of an installation.

■ Transient overvoltage represents a higher risk for more advanced technology. This is due to the fact that components tend to be smaller and more sensible to overvoltage.

3.2 Lightning Risk and Protection Assessment Procedure

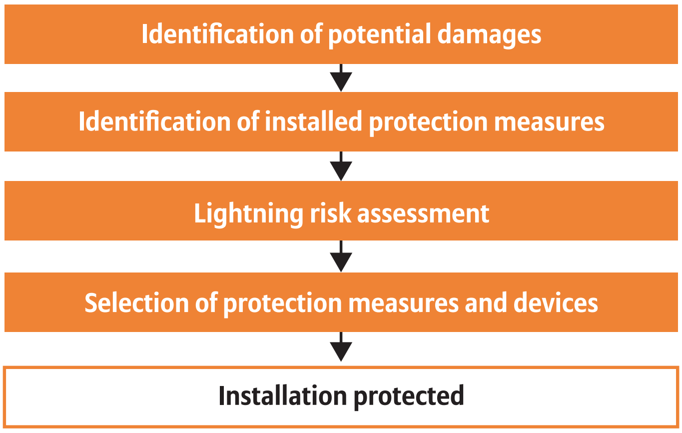


Figure 22 *- Steps of the lightning protections assessment process*

Step 1: Identification of Potential Damages (Type of equipment)

3.2.1 Equipment Classification – Overvoltage Categories

- These categories differentiate the degrees of overvoltage that each component of an electrical installation, equipment, and/or appliances is able to withstand
- Categories indicate the voltage value allowed and the maximum value of residual current
- Concept used for equipment directly connected to the low voltage main grid
- Four overvoltage categories: Category I – IV

Category I
- Equipment connected to circuits aiming at taking measurements to limit transient overvoltage.
- The mitigation measures should ensure temporary overvoltage is sufficiently limited.
- Example: Equipment for connection to circuits in which measures are taken to limit transient overvoltage to an appropriately low level. Equipment under category I cannot be directly connected to the supply mains.

Category II
- Energy-consuming equipment supplied from the fixed installation.
- Example: Appliances, portable tools, and other industrial and household loads

Category III
- Equipment for cases where the reliability and availability of the equipment is subject to special requirements.
- Example: Switches in fixed installations and other equipment for industrial use with permanent connection to the fixed installation.

Category IV

- Equipment to be used at the origin of the installation.
- Example: Electricity meters and primary overcurrent protection equipment.

→ Depending on the nominal voltage of the installation, the impulse withstand value will vary with the category of the overvoltage.

Rated voltage of the installation (V)		Required impulse withstand voltage (kV)			
3- phase systems	Single phase	Cat IV	Cat III	Cat II	Cat I
230/400	120 - 240	4	2.5	1.5	0.8
277/480	-	8	4	2.5	1.5
400/690	-	8	6	4	2.5
1000	-	Values subject to system engineers			

Table X *- Required impulse withstand voltage depending for each overvoltage category*

Step 2: Identification of Installed Lightning Protection Measures

The types of external lightning protection measures installed on the location of the PV plant will influence the requirements of protective measures.

Three possible scenarios:

- **Scenario 1:**
  External Lightning Protection System installed in the building.
  PV generator can keep the security distance.

- **Scenario 2:**
  External Lightning Protection System installed in the building.
  PV generator closer than security distance.

- **Scenario 3:**
  No external Lightning Protection System

Step 3: Risk assessment calculation (IEC 60364-7-712)

Required information:

- Lightning ground flash density at the location of the PV plant
- Maximum route length of the cable between power conversion equipment and connections of the PV modules.

The method followed is based on the evaluation of the critical length.

The critical length (**Lcrit**) depends on the type of PV installation, and is calculated according to Table 7. Other variables used for the risk assessment calculation are:

- **Ng** is the lightning ground flash density (flash/km²/year) relevant to the location of the power line and connected structures. This value may be determined from ground flash location networks in many areas of the world.

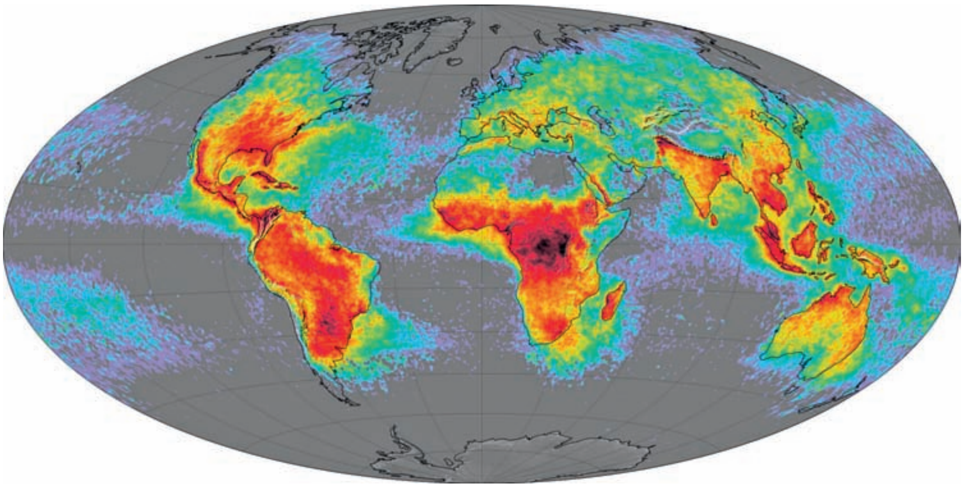


Figure 23 - *World lightning map (Source: NASA)*

- **L** (m) is the maximum route length between the power conversion equipment (PCE) and the connection points of the PV modules of the different strings.

$$\text{Lcrit [m]} = \begin{cases} \dfrac{115}{Ng} & \text{; for PV installations attached to a building} \\ \dfrac{120}{Ng} & \text{; PV installations not attached to a building.} \end{cases}$$

If $L \geq$ Lcrit → SPD(s) are required on the DC side

Results

- Based on this method, if L is larger than Lcrit calculated for a particular installation, adequate surge protection measures (SPDs) are required.

  Overvoltage protection is always a compromise between the probability of an event, the cost of protection equipment and the value of the potential damage to the equipment we want to protect. Once the risk has been assessed, if required, SPDs will be selected.

Example: Calculation of the critical length for a PV plant on a building in a Mediterranean city like Barcelona.

- Iso-keraunic information

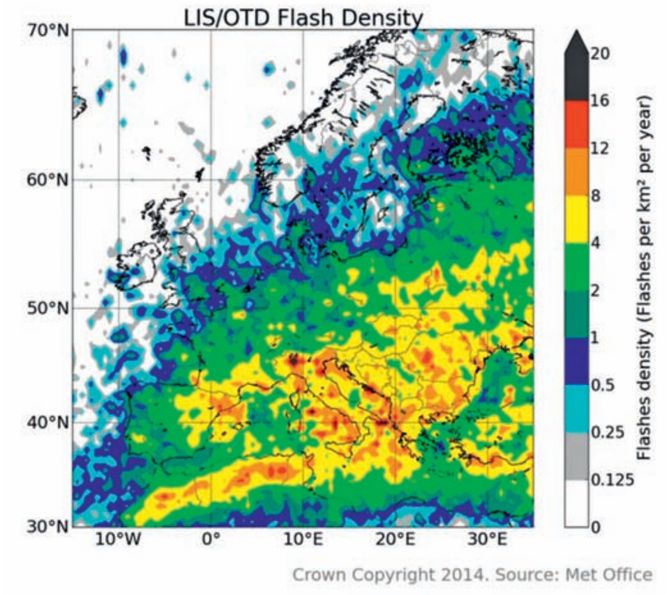


Figure 24 *- Iso-keraunic map of Europe (Source: Met Office)*

- According to the figure above, in Barcelona, the keraunic number is approximately 10. Ng = 10.

- Therefore: Lcrit = 115 / 10 = 11.5 m

Consequently, if the distance between the power conversion equipment and the connection points of the PV module is 11.5 meters or more, adequate SPDs are required.

Relevant Information and Considerations when Determining the Risk

- The installation of PV modules does not increase the risk of a lightning strike, but interference may be injected on to the building through a PV plant.
- Important to differentiate between general electrical installations and PV plants, since following the standard electrical installations requires a more complex risk analysis, provided in IEC 62305
- Protective measures for the DC side of the PV plant must be specifically designed to carry out this function (The manufacturer shall provide the relevant information).
- Power conversion equipment may already have embedded protective measures on the DC side. (The manufacturer shall provide the relevant information.)
- Once the risk has been assessed, protective measures are selected (SPDs).
- Typically, SPDs will be Type 2. If an external LPS is installed, and the separation distance is not kept, Type 1 SPDs shall be installed together with Type 2 or combined Type 1+2.

Calculation of the Minimum Separation Distance (IEC 62305-3)

Electrical isolation between air terminals, down-conductors, and metallic parts of the structure, and internal systems will be ensured if a security distance ***s*** is kept between these parts. The separation distance should be bigger than the security distance:

$$s = \frac{k1}{km} \times kc \times l$$

Where

k1 depends on the class of LPS

k2 depends on the electrical isolation of the materials

kc depends on the current (partial) circulating through the air terminals and down-conductors

l is the distance (in meters) from the point we are measuring separation distance to the closest equipotential bonding point.

→ *Values for k1, k2, and kc are provided in IEC 62305-3*

- The value of Up will be below 80% of the value of the impulse to be able to withstand voltage from the equipment to be protected.
- If no information is provided, Table XI determines preset withstand voltages.

$U_{OC\,max}$ of PV generator (V)	U_W (kV)	
	PV module	Power conversion unit
100	0.8	-
150	1.5	-
300	2.5	-
400	-	3.1
600	4	4.2
800	-	5.1
1000	6	5.6
1500	8	8.5

***Table XI** - Impulse withstand voltage to be used when no information is available (Source: IEC 60364-7-714)*

- The value of the maximum voltage acceptable by the surge protective device shall be selected according to the open-circuit voltage of the PV generator. Thus, the SPDs will be selected with regard to the maximum voltage between:
• Live terminals
• Live terminals and earth

- The minimum value of the nominal discharge current ***In*** will be 5 kA.

- In case Type 1 SPDs are required, the impulse current should be at least 12.5 kA.

- SPDs in the DC side should be installed close to the electronic equipment (power conversion, string surveillance transducers, etc). If a very high protection level is needed, SPDs can be connected together (e.g. creating a Type 1+2 SPD) (According to IEC 60364-7-712).

- The surge voltage level on the equipment depends on its distance from the SPD. If the equipment is separated by more than 10 meters, the value of the surge voltage may be doubled due to the effect of resonance.

- For DC SPDs connections to the main earthing terminal, conductors will have a cross section of at least 6 mm^2 for Type 2, and 16 mm^2 for Type 1.

Step 4: Selection of Protection Measures and Devices

The Surge Protection Device is a protection component of the electrical installation. SPDs are usually connected in parallel with the equipment that needs to be protected. However, it can also be used at all levels of the power supply grid.

SPDs eliminate the following overvoltage:
- Common mode overvoltage
- Differential mode overvoltage

3.2.2 Types of SPDs – Classification

There are three different types of SPDs:

Type 1
- Recommended for the case of service-sector and industrial buildings protected by a lightning protection system or a meshed cage
- Protects electrical installations against direct lightning strikes
- Discharges the back-current coming from the earth conductor
- Characterized by 10/350 µs current wave

Type 2
- Main protection system for all low voltage electrical installations
- Prevents the spread of overvoltage into electrical installations and protects the loads
- Characterized by 8/20 µs current wave

Type 3
- Low discharge capacity
- Mandatorily installed as a supplement of Type 2
- Characterized by a combination of voltage waves (1.5/50 µs) and current waves (8/20 µs)

3.2.3 SPD Normative Definition

	Direct lightning strike	Indirect lightning strike	
IEC 61643-1	Class I test	Class II test	Class III test
IEC 61643-11/2011	Type 1 (T1)	Type 2 (T2)	Type 3 (T3)
EN/IEC 61643-11	Type 1	Type 2	Type 3
Former VDE 0675v	B	C	D
Type of test wave	10/350	8/20	1.2/50 + 8/20

***Table XII** - Classification of recommended SPD type for direct and indirect lightning strikes*

3.2.4 Characteristics of SPDs

General Characteristics

For the SPD to be installed properly, the correct values have to be chosen. There are three parameters that describe all SPDs.

- Uc: Maximum continuous operating voltage. The voltage above which the SPD will be activated. Depends mainly on the rated voltage magnitude and if it is AC or DC.
- Up: Voltage protection level (at In). As described previously, there are different overvoltage categories at which the loads will be capable to withstand. This Up value is the maximum voltage that will appear across the SPD given an In value, thus the overvoltage category of the equipment shall be higher than Up to avoid any damage.
- In: Nominal discharge current. Peak value of waveform 8/20 (Type 2) that SPD will be capable of withstanding for **20 times**.

Specific Characteristics

Type 1

- I_{imp}: Impulse current. Peak value of 10/350 waveform that SPD can discharge five times. IEC 62305 standard requires 25kA per pole – 100kA per 3P+N system.
- I_{fi}: Auto-extinguish follow current (only for spark gap devices). Current that SPD will be able to cut after the overvoltage activation. It has to be higher than the short circuit capacity at the installation point.

Type 2

- I_{max}: maximum discharge current. Peak value of 8/20 waveform that SPD can discharge once.

Type 3

- U_{oc}: Open circuit voltage applied at the tests

3.2.5 Use of SPDs

Main decisions-procedures to be taken for properly designing the overvoltage protections for the electrical installation:

Basic Design Rules

The first decision to be taken depends on whether there is a lightning protection system in the same building or not.

If the answer is yes, Type 1 SPD has to be installed at the building's network origin.

Whether the answer is yes or no, Type 2 SPD has to be installed if protection is decided. This will protect the installation from induced overvoltage.

Finally, if there is a presence of sensitive equipment and the distance between them and the board is more than 10 meters, Type 3 SPD should be installed.

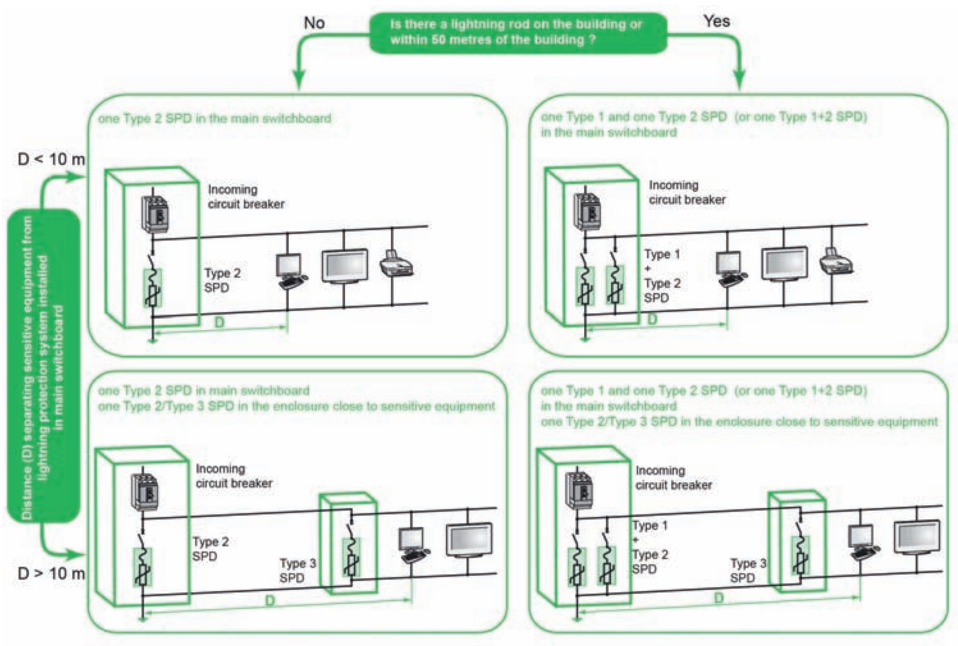


Figure 25 - *Proposed process for selecting SPD type (Source: Schneider Electric)*

Characteristics Selection for SPDs

According to IEC 60364, the minimum values for an SPD installed at the incoming end of the installation are:

In = 5kA (8/20),

Up (at In) < 2.5kV.

However, depending on the type, additional considerations need to be taken:

• Uc – Operating Voltage

On the AC side, the maximum operating voltage will depend on the system's neutral configuration. The next table schematizes the decision of Uc for the SPDs.

SPD connected between	System configuration of distribution network				
	TT	TN-C	TN-S	IT with distribute d neutral	IT without distributed neutral
Line conductor and neutral conductor	1.1 Uo	NA	1.1 Uo	1.1 Uo	NA
Each line conductor and PE conductor	1.1 Uo	NA	1.1 Uo	√3 Uo	Vo
Neutral conductor and PE conductor	Uo	NA	Uo	Uo	NA
Each line conductor and PEN conductor	NA	1.1 Uo	NA	NA	NA
NA: not applicable					
Note 1: Uo is the line-to-neutral voltage, Vo is the line-to-line voltage of the low voltage system. Note 2: This table is based on IEC 61643-1 amendment 1.					

Table XIII – *Stipulated minimum value of Uc for SPDs depending on the system earthing arrangement (based on Table 53C of the IEC 60364-5-53)*

However, the most common values for Uc chosen are:

- For TT and TN: 260, 320, 340, 350 V.
- For IT: 440, 460 V.

• Up (at In) – Voltage Protection Level

Despite the minimum Up of 2.5kV for most common application, Table 13 describes the need of more accurate SPDs for especially sensitive equipment.

• Number of Poles

To assure protection in common mode and differential mode overvoltage, SPDs have to be installed between phases and neutral and neutral to earth. Only in an IT distribution system, phase-neutral protection is not needed and in TT and TN-S is recommended but not compulsory.

Type 1

• I_{imp}: The minimum value for I_{imp} is 12.5kA (10/350) according to IEC 60364-5-534. However, a classification exists based on the capacity of the lightning protection system to dissipate the energy.

Protection level as per EN 62305-2	External lightning protection system designed to handle direct flash of:	Minimum required Iimp for Type 1 SPD for line-neutral network
I	200 kA	25 kA/pole
II	150 kA	18.75 kA/pole
III/IV	100 kA	12.5 kA/pole

Table XIV - *Table of I_{imp} values according to the building's voltage protection level (based on IEC 62305-2)*

• **I_{fi} :** Higher than the short circuit capacity at the point of installation, only for spark gap technology.

Type2

• **I_{max}:** maximum discharge current

This parameter is defined according to the risk relative to the building's location. See the table below for an approximated value of that parameter.

	Exposure level		
	Low	Medium	High
Building environment	Building located in an urban or suburban area of grouped housing	Building located in a plain	Building where there is a specific risk: pylon, tree, mountainous region. Wet area or pond.
Recommended Imax value (kA)	20	40	65

Table XV - *Risk relative to the building's location*

• Short Circuit Protection Device (SCPD)

After repeated activation, or due to ageing, the SPD will reach the end of its service lifetime. Usually this has no dangerous consequences since the SPD has an internal disconnector that disables it.

However, a faulty SPD or any mistake in design may lead to a non-protected short circuit.

Therefore, an SCPD has to be installed upstream of the SPD. It can either be a fuse or a MCB. Some commercial solutions include SCPD in the device so there is no need to use an additional MCB or fuse. In case the upstream installed SCPD has a higher current rating than the value specified in the SPD datasheet as maximum back-up fuse, an SCPD with a lower rating than that maximum value has to be installed directly upstream the SPD and consequently in parallel with the rest of the installation.

Installation recommendations:

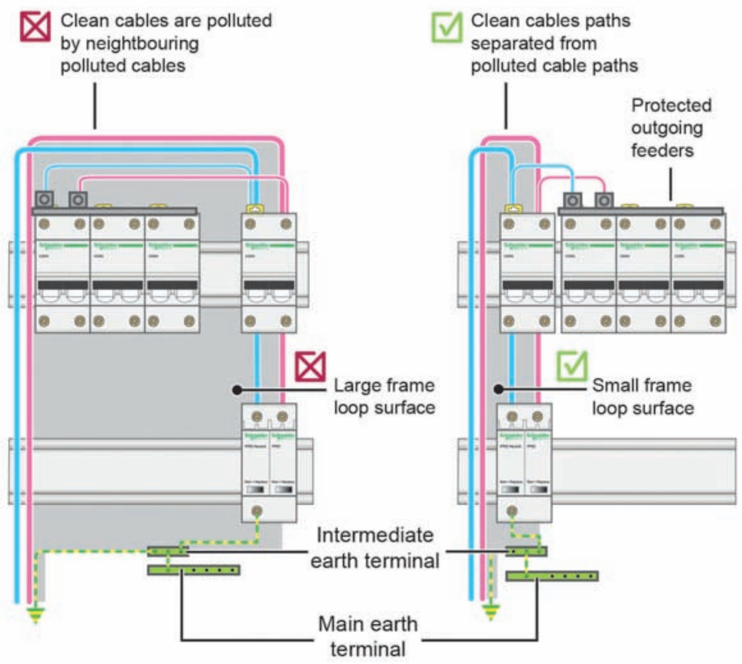


Figure 26 *- Recommendation for electric switchboard wiring (Source: Schneider Electric)*

In the particular case of surge protection for photovoltaic generators, on the DC side, this requirement may not be mandatory in case there is a short circuit current in the PV plant (Isc is equal to or lower than the short circuit withstand current value in the SPD, Iscwpv.) In particular, values of Iscwpv around 5 to 10 kA offered by some manufacturers guarantee that an additional SCPD will not be needed.

3.3 Example Case Scenarios

In this guide, there are three scenarios considered as examples:
- Case 1: Building without external lightning protection system
- Case 2: Building with external LPS and sufficient separation distance
- Case 3: Building with external LPS and insufficient separation distance

Case 1: Building without External Lightning Protection System

- Building without a lightning protection system
- Outline of the building is not considerably changed→ Lightning frequency remains the same → No specific measures against this risk are necessary.

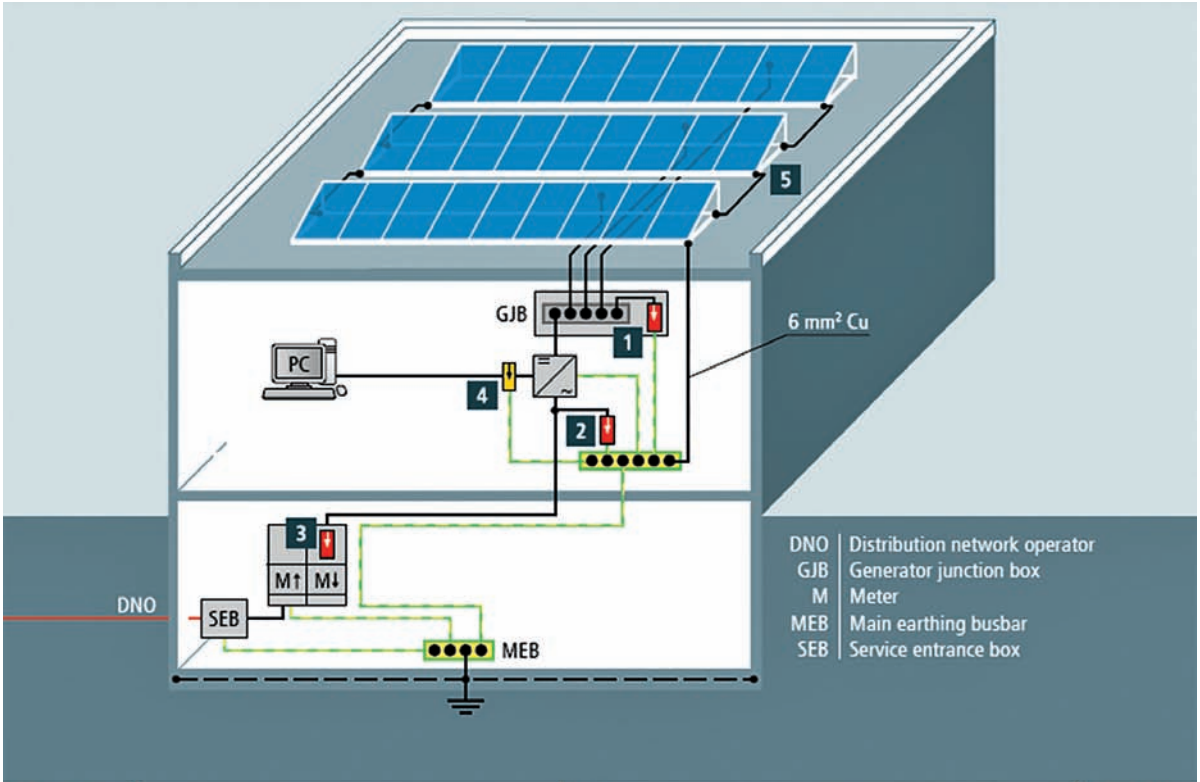
Risks of Case Scenario 1

The risk of this scenario is that dangerous surges can enter the PV generator due to inductive coupling and then can transmit it over the rest of the installation.

Protective Devices

Type 2 SPDs are required for:

- DC side of the plant (close to each MPPT input of the power conversion unit; if distance between array and power conversion unit is >10 m, one or more SPDs should also be added close to the array).
- AC output of power conversion units (unless distance between power conversion unit and SPD at the grid point is less than 10 m)
- Main LV distribution board
- Wired communication interfaces



No. in Fig.		SPD * FM = Floating remote signalling contact	Part No.
d.c. input of the inverter			
1	Per MPPT	DEHNguard DG M YPV SCI 1000 FM *	952 515
	For 1 MPPT	DEHNcube DCU YPV SCI 1000 1M	900 910
	For 2 MPPTs	DEHNcube DCU YPV SCI 1000 2M	900 920
a.c. output of the inverter			
2	TN-S system	DEHNguard DG M TNS 275 FM *	952 405
Low-voltage input			
3	TN-C system	DEHNguard DG M TNC CI 275 FM *	952 309
	TN-S system	DEHNguard DG M TNS CI 275 FM *	952 406
	TT system	DEHNguard DG M TT CI 275 FM *	952 327
Data interface			
4	Two pairs, even with different operating voltages up to 180 V	BLITZDUCTOR BXTU ML4 BD 0-180 + BXT BAS base part	920 349 + 920 300
Functional earthing			
5	Functional equipotential bonding	UNI earthing clamp	540 250

Figure 27 *- Case 1: Building without external LPS (Source: Dehn)*

Protections on the DC Side

- Every DC input of the power conversion unit (or PV charge controller in some type of PV plants with batteries) must be protected by a Type 2 SPD
- In case there is a combiner box between the PV strings and the power conversion unit, one SPD can be installed per combined MPPT input (in the combiner box) as long as the total distance between the power conversion unit and the array adds up to less than 10 meters. If the total distance is more than 10 meters, an additional SPD should be added at each of the power conversion unit's MPPT inputs, assuming that the aforementioned combiner box is usually closer to the PV array (<10 meters); if the combiner box is farther than 10 meters from the PV array, the SPDs protecting the latter cannot be installed in the combiner box, but should be placed rather close to the PV array. The aforementioned statement is applicable to all three scenarios

Protections on the AC Side

- It is considered sufficiently protected if the distance between the PV power conversion units and the place of installation of the Type 2 SPD at the grid connection point is less than 10 meters.
- In case there are more than 10 meters, additional Type 2 SPDs should be installed at the AC output of the power conversion unit.

Protections Devices at the Main LV Distribution Board

- Type 2 SPD must be installed upstream of the meter on the low-voltage in-feed.
  - > Circuit Interruption (CI) is a coordinated fuse integrated in the protective path of the arrester
  - > It allows the arrester to be used in the AC circuit without additional backup fuse.
  - > It is available for every type of earthing system configuration
    - TT, TN, IT

Protections at Wired Communication Interfaces

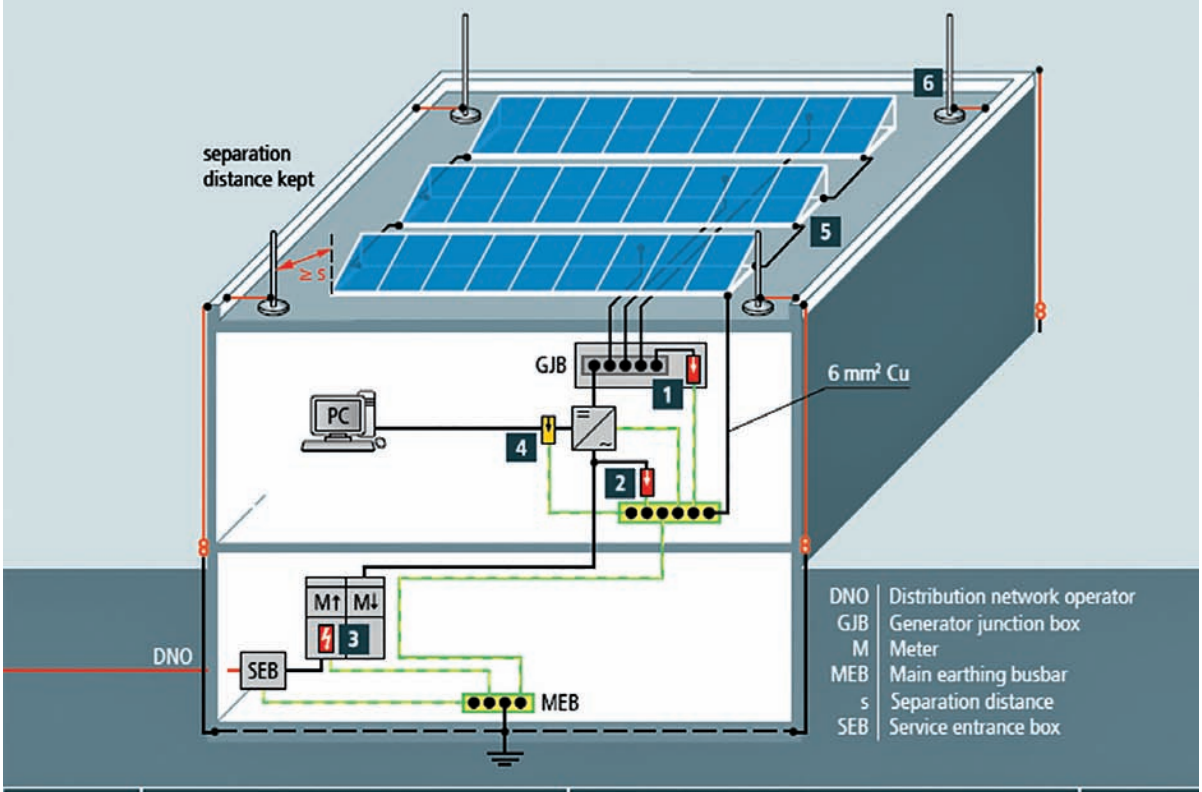
- If power conversion units are connected to data and sensor lines, suitable SPDs should also be installed.

Case 2: Building with External Lightning Protection System (LPS) and Sufficient Separation Distance

- Building with external LPS is installed on the rooftop
- Security distances are respected

The main functions of the LPS and surge protection measures are to avoid damage to structures and property (by fire), and to persons.

It is important to ensure that the PV generator does not interfere and is protected by the external LPS.



No. in Fig.		SPD * FM = Floating remote signalling contact	Part No.
d.c. input of the inverter			
1	Per MPPT	DEHNguard DG M YPV SCI 1000 FM *	952 515
	For 1 MPPT	DEHNcube DCU YPV SCI 1000 1M	900 910
	For 2 MPPTs	DEHNcube DCU YPV SCI 1000 2M	900 920
a.c. output of the inverter			
2	TN-S system	DEHNguard DG M TNS 275 FM *	952 405
Low-voltage input			
3	TN-C system	DEHNventil DV M TNC 255 FM *	951 305
	TN-S system	DEHNventil DV M TNS 255 FM *	951 405
	TT system	DEHNventil DV M TT 255 FM *	951 315
Data interface			
4	Two pairs, even with different operating voltages up to 180 V	BLITZDUCTOR BXTU ML4 BD 0-180 + BXT BAS base part	920 349 + 920 300
Functional earthing / External lightning protection system			
5	Functional equipotential bonding	UNI earthing clamp	540 250
6	Air-termination system	Air-termination rod with concrete base (8.5 kg)	101 000 + 102 075

Figure 28 - *Case 2: Building with external LPS and sufficient separation distance*

Determination of the Protected Volume by the LPS

- Two methods
  - >The rolling sphere method (Figure 27)
  - > The angle method (Figure 28)

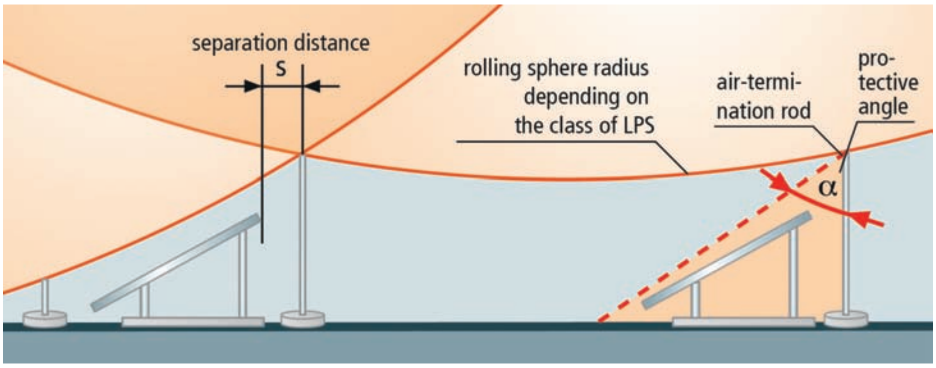


Figure 29 - *Rolling sphere method example (Souce: Dehn)*

Figure 30 - *Angle method example (Source: Dehn)*

- A certain separation distance must be maintained between all conductive parts of the PV generator and the LPS to prevent core shadows and induced overvoltage and dangerous arcing.
- Induced overvoltage will appear if the distance is not respected due to the large electromagnetic fields caused by lightning current through down-conductors of the LPS.

Types of Protections

At the grid connection point:
- Type 1 SPD will be installed if the distance from the grid connection point to the power conversion unit is less than 10 meters
- If the distance is larger than 10 meters, an additional Type 2 must be installed upstream the AC input of the power conversion unit, as close as possible to the AC output of the power conversion unit.
- The additional Type 2 SPD is required in case the distance is bigger because, by the resonance effect, the value of the transient wave can double after these 10 meters.
- Every DC input of the power conversion unit must be protected by a Type 2 arrester (also applies to transformerless devices)
- If power conversion units are connected to data lines, SPDs must also be installed.

In case it is impossible to maintain the security distance, another option for protection is installing high-voltage-resistant insulated HVI conductors. These conductors allow maintaining a separation distance up to 0.9 meters in the air.

Case 3: Building with External LPS and Insufficient Separation Distance

In case:

- Roofing is too small
- Made out of metal
- Formed by the PV system

Separation distance cannot be kept.

- If separation distance cannot be maintained: metal components of the PV mounting system must be connected to the LPS through a conductor with a cross-section of at least 16 mm^2.

> Lightning equipotential bonding must be implemented for the PV lines entering the building

> Each MPPT input should be protected by a nearby/integrated Type 1+2 SPD. If the distance between the power conversion unit and the connected arrays is greater than 10 meters, additional SPDs are required close to the PV array.

> If PV power conversion units are separated more than 10 meters from the Type 1 SPD installed at the grid connection point, Type 1 and Type 2 SPDs or combined Type 1+2 are recommended to be installed on the AC side of the power conversion unit

> Suitable surge protection devices must also be installed to protect the relevant data lines for yield monitoring

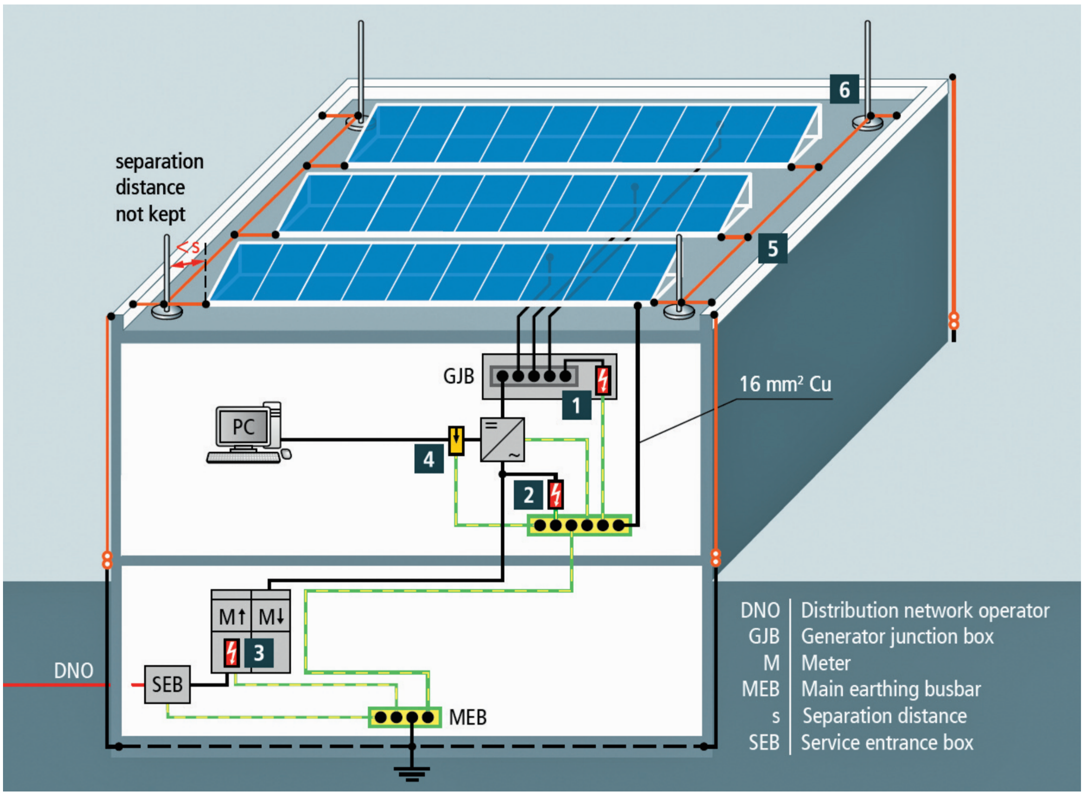


Figure 31 - Case 3: Building with external LPS and insufficient separation distance

Case of Ground PV Plants

For PV plants erected on the ground, the likelihood of losses due to fire caused by a lightning strike decreases considerably, whereas step and touch voltages represent main risks to people. In this case, an important factor is surface resistivity. If this exceeds 5 k , it is not necessary to take any particular measure since the touch and step voltage values are negligible. However, if soil resistivity is equal or lower than 5 k m, it is important to verify whether measures against step and touch voltages are necessary. This is especially important for very large plants since the probability of lightning strikes will be higher as well.

3.4 Notes About Relevant Regulation

- Due to the negligible effect on the increase of probability of a direct lightning strike to PV generators on a building, it does not necessarily require a lightning protection system if none is already present
- In case the physical characteristics or prominence of the building do change significantly, it is recommended to carry out a risk assessment according to IEC 62305-2 standards, and if required, install a lightning protection system according to IEC 62305-3.
- If there is a lightning protection system (LPS) already installed, the PV generator should be integrated into the LPS according to IEC 62305-3.
- Even if there is no LPS installed, overvoltage protection may still be required to protect the PV generator and the power conversion unit.

- Protection against overvoltage:
  - All DC cables should be installed so that positive and negative cables are bundled together, avoiding loops in the electrical layout.
  - Long cables (e.g. PV main DC cables over 50 meters) should either be:
    - > Installed in earthed metallic conduit or trunking, where the conduit is connected to the equipotential bonding
    - > Be buried in the ground
    - > Cables incorporating mechanical protection which will provide a screen where the screen is connected to the equipotential bonding
    - > Be protected by a SPD

- Surge Protection Devices (SPD)
  - DC Side
    - > SPDs shall be compliant with EN 50539-11 and be explicitly rated for the use on the DC side of a plant
    - > If the PV plant is connected to other incoming networks (such as telecommunication or signaling services) SPDs will be required to also protect the information technology equipment.

Annex I: Complete Risk Assessment Process for PV Plants

In order to identify and categorize the risks inherent to a PV plant, there are a number of steps to be followed.

IEC 62305-2 provides a complete methodology for carrying out a risk assessment before designing and installing a low voltage electrical installation.

According to the methodology proposed, the steps to calculate the risk from overvoltage caused by meteorological events are the following:

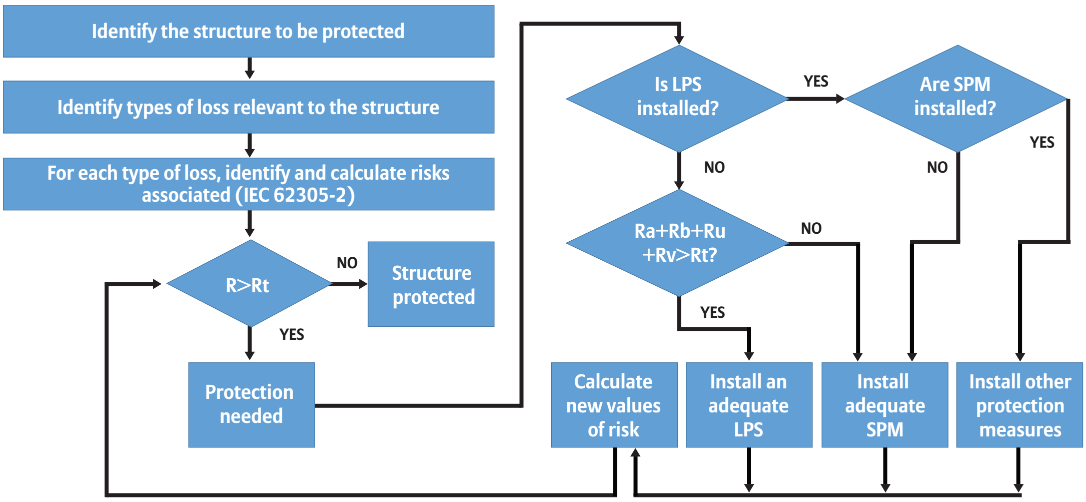


Figure 32 - Risk Assessment methodology IEC 62305-2

In this methodology, there are two cases and four types of risk considered:

- Case A: Direct lightning to a structure
  - Ra: Risk of injury to living beings caused by electric shock
  - Rb: Risk of physical damage

- Case A: Direct lightning to an incoming line
  - Ru: Risk of injury to living beings caused by electric shock
  - Rv: Risk of physical damage

To calculate ***R***, the cases of indirect lightning to both a structure and an incoming line are also considered.

It is important to note that the level of risk will be modified by LPS lightning protection level (LPL), as well as by the type and number of SPDs already installed, among many other factors.

For more information regarding this procedure, please refer to the IEC 62305.

4.

OTHER TRANSIENT OVERVOLTAGE

Due to the existence of switching operations or a sudden connection or disconnection of large loads, dangerous transient overvoltage events can appear on clients' internal grid. These events are frequent in Lebanon due to the frequent switchover between utilities. There are some cases in industrial installations in Lebanon where the observation of switch over overvoltage has been reported.

Therefore, since transient overvoltage generated due to switching operations can make the protections trip, it is recommended to carry out an assessment of transient overvoltage. For this purpose, a very simple methodology is proposed in the following part of the guide.

4.1 Assessment Process

The assessment of other types of transient overvoltage basically aims at identifying and modeling the waves of these overvoltage events.

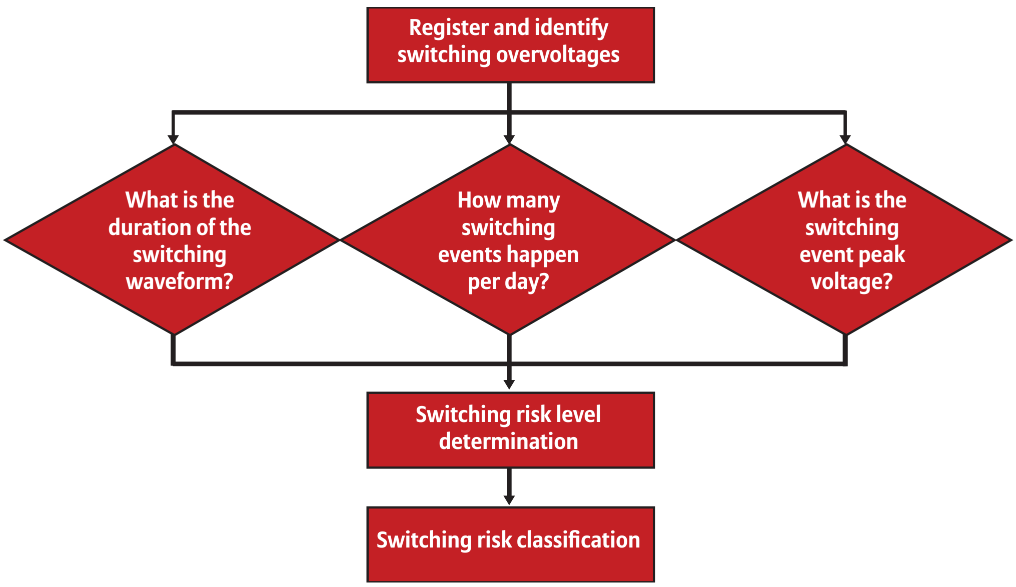


Figure 33- *Switching operations risk assessment method*

In order to identify and model the waveforms and wavelengths of the transient overvoltage due to switching and other causes, it is necessary to monitor the connection where the PV plant will be installed for a number of days (two or three is recommended) and analyze voltage and frequency variations of voltage as well as the number of transient events happening per day. This can be done by means of a grid analyzer.

The proposed indexes for classifying these types of overvoltage, are:
- Duration of the switching wave in µs
- Number of transient overvoltage events (#/day)
- Peak voltage of the switching wave in volts

This information should then be used to set a risk level and to classify it as well as to select adequate surge protection measures in case it is necessary.

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