TECHNICAL GUIDELINES FOR
THE INSTALLATION OF PHOTOVOLTAIC MINI-GRIDS

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TECHNICAL GUIDELINES FOR **THE INSTALLATION OF PHOTOVOLTAIC MINI-GRIDS**

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Foreword

The Economic Community of West African States (ECOWAS) was established on 28th May 1975 by Heads of States and Governments of fifteen (15) Member States as an Economic Community of the Region. The treaty was reaffirmed in 1993.

One of the important mandates of ECOWAS is to promote the establishment of a Common Market, the harmonization of Standards and conformity assessment procedures and measures to reduce Technical Barriers to Trade, encourage intra and international Trade as well as enhance the industrialization of the region.

The ECOWAS Heads of State and Governments, at its 43rd Ordinary Session, from 17 to 18 July 2013 in Abuja, Nigeria, renewed their commitment to the provision of sustainable energy services in ECOWAS by adopting the ECOWAS Energy Efficiency Policy (EEEP) which aims to implement measures that will save up to 2000 MW of power generation capacity by 2020. To achieve the objectives of the ECOWAS Energy Efficiency Policy, several flagship initiatives were established, among which the ECOWAS Initiative on Standards and Labeling, which aims to adopt region-wide standards and labels for major energy appliances and equipment.

ECOWAS Standards are drafted in accordance with the rules given in the ISO/IEC Directives, Part 2.

The work of preparing ECOWAS Standards is normally carried out through ECOWAS Technical Committees. Each member body interested in a subject for which a Technical Committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ECOWAS, also take part in the work.

The main task of the Technical Committees is to prepare ECOWAS Standards. Draft ECOWAS harmonized Standards adopted by the Technical Committees are circulated to the member states for voting. Publication as an ECOWAS Standard requires approval by at least 75% of the member states casting a vote.

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. ECOWAS shall not be held responsible for identifying any or all such patent rights.

AFSEC Foreword

The African Electrotechnical Standardization Commission (AFSEC) was established inter alia to improve the wellbeing of the African population, mainly by the promotion, development and application of harmonized standards on the entire continent in order to improve access to electricity. To achieve these objectives, AFSEC has the mission to:

- Identify existing standards and prioritize the needs of members of AFSEC with regard to standardization;
- Harmonize the existing standards, by adopting international standards, or in case of need, adapting them to the African conditions;
- Identify in case of need, the draft standards to be considered by the members of AFSEC for the purpose of adopting them;
- Make recommendations on the harmonized standards for their application by relevant Regulatory bodies.

Recognizing the need for an appropriate guide for mini-grid installation in Africa, AFSEC TC 64, which is a mirror committee of IEC TC 64, was tasked to develop Technical Guidelines for Photovoltaic (PV) Mini-grid Installations. The committee decided to reference existing regulations and IEC standards to facilitate the project.

The Guide covers regulatory frameworks, system design principles, component selection, installation practices, testing and commissioning procedures, maintenance guidelines, safety precautions, and documentation requirements.

Introduction

Photovoltaic (PV) mini-grids are pivotal in extending electricity access to remote areas, enhancing energy security, and fostering sustainable development. To ensure safe, efficient, and standardized installations, the African Electrotechnical Standardization Commission (AFSEC) has developed comprehensive guidelines covering key aspects of PV mini-grid inspections. These guidelines serve as a foundational framework for stakeholders involved in the inspection of PV mini-grid systems across the African continent. This guideline provides verification into the following functionalities and safety of PV installations.

Planning and Site Assessment: Before installation, meticulous planning and site assessment are imperative. AFSEC guidelines emphasize the significance of thorough site evaluations encompassing solar irradiance analysis, topographical surveys, load assessments, and environmental impact considerations. Comprehensive planning ensures optimal system sizing, layout design, and resource utilization.

Design and Engineering: AFSEC underscores the importance of robust design and engineering practices to ensure system reliability, performance, and longevity. Guidelines outline criteria for PV module selection, inverter sizing, battery storage configuration, and system protection mechanisms. Adherence to design standards mitigates technical risks and enhances system efficiency.

Installation and Commissioning: Installation procedures must adhere to stringent quality and safety standards outlined by AFSEC guidelines. Proper installation of PV modules, mounting structures, wiring, and balance of system components is paramount. Additionally, commissioning procedures encompass system testing, performance validation, and user training to ensure seamless operation and functionality.

Operation and Maintenance: Sustainable operation and maintenance practices are integral to the longevity and performance of PV mini-grid systems. AFSEC guidelines advocate for routine inspection, cleaning, and monitoring of system components to detect faults, optimize performance, and maximize energy yield. Training programs for local technicians facilitate timely troubleshooting and maintenance activities.

Safety and Compliance: Safety protocols are paramount throughout the installation lifecycle to mitigate hazards and ensure personnel and community well-being. AFSEC guidelines emphasize adherence to electrical safety standards, fire prevention measures, and structural integrity requirements. Compliance with relevant regulatory frameworks and permitting processes is essential for legal and operational compliance.

Community Engagement and Capacity Building: Effective community engagement fosters local ownership, acceptance, and sustainability of PV mini-grid projects. AFSEC guidelines advocate for stakeholder involvement, awareness campaigns, and capacity-building initiatives to empower local communities. Inclusive approaches promote socioeconomic development, energy equity, and environmental stewardship.

In conclusion AFSEC's PV mini-grid inspections guidelines provide a comprehensive roadmap for inspectors to navigate the complexities of deploying sustainable electrification solutions across Africa. By prioritizing safety, quality, and community empowerment and eventual issuance of certificates and permits, that will pave the way for scalable, resilient, and inclusive energy access initiatives, driving socioeconomic transformation and advancing the continent towards a sustainable energy future.

1 SCOPE

This guide provides an overview of standards related to the design and installation of photovoltaic (PV) mini grids. It defines the design and installation requirements for photovoltaic systems with or without storage and an optional backup generator for the supply of stand-alone and/or grid-connected mini-grids systems. It is aimed at stakeholders involved in PV mini-grid projects design and installation by guiding them to ensure adherence to relevant international and local standards thereby promoting safe, efficient, compliant and sustainable installations.

In order to comply with the vast majority of systems in operation or under development, the guide focuses on systems with the following characteristics:

- The output power of the multifunctional inverter and PV generator is in the low-voltage regime, single-phase and three-phase.

- **The nominal continuous output power at 25°C of the PV system is between 3 kW and 1000 kW LV consolidated with MV integration on larger installations.** The nominal output power can be provided by a set of multifunctional parallel inverters operating in inverter mode (one a master), with or without a back-up generator, and possibly a set of PV inverters only depending on the configuration chosen. When in the off-grid mode, the inverter needs to have grid forming capability.

- When the only source of producing energy is with PV modules, the designed load regime needs to be compatible with the seasonable daily solar irradiance, considering the weather limitations.

- The charging of the storage battery via the DC bus is carried out by one or more **MPPT photovoltaic charge controllers** or by DC generator/converter. The MPPT could be integrated into the mufti-functional inverter.

- The charging of the battery via the AC bus is carried out by one or more sets of **"multi-functional inverters"** in case there are PV inverters and/or AC back-up generators with battery chargers.

- A mini-grid could consist of a plant without PV modules, only a battery and inverter, but then it needs to have a grid connection and/or a back-up generator.

- Voltage range on the DC side, both PV and DC bus:
  - ELV: 0 V < UDC ≤120 V
  - LV: 120 V < UDC ≤ 1500 V

- Voltage range on the AC side:
  - ELV: 0 V < UAC ≤50 V
  - LV: 50 V < UAC ≤ 1000 V

- Electricity generation and storage are centralized at a single location (however, the prescriptions remain valid for a decentralized PV generator connected to the AC bus of the same grid).

- Photovoltaic technology **is mainly based on crystalline silicon**, which today accounts for the vast majority of photovoltaic systems in mini-grids, bearing in mind that other technology options are also available.

- The technologies used preferably should **not connect any polarity to the earth, neither on the PV side nor on the DC bus side.** However, for functional reasons, some photovoltaic technologies require a polarity of the PV array to be earthed. This earthing may be permissible subject to compliance with the requirements of IEC 60364-7-712. In some very special cases of LV Li-ion storage batteries, some manufacturers may recommend earthing the negative polarity of the DC bus. In this case, all the recommendations related to the safety of people and equipment must be proposed by the manufacturer in accordance with IEC 60364-7-712 standard and IEC 61200. standards.

- This guide **deals with protection against direct lightning impact** through the use of lightning arresters.

- This guide deals primarily with lithium-ion battery technology but other technologies can also be used as subject to the safety requirements recommended by international best practices standards.

The guide **does not address issues relating to electricity distribution** (transformer, distribution network, user interface, metering, etc.) although LV interconnection is applicable subject to the design being within best safety practices for LV systems.

Energy sizing rules (calculation of peak PV capacity, inverter and generator power, and storage capacity) are out of the scope. They depend on local climatic conditions, the analysis of the electrical energy demand and the available budget.

Important note in the case of power transmission in the medium-voltage regime:

In the case of having a power distribution through a MV network via several LV/MV transformers, it is important to note the significant risk of malfunctioning due to the magnetization phenomena of the transformers. When starting-up a transformer under load (with active loads), the magnetization current of the windings can reach up to 10-100 times the nominal current of the transformer. Unlike rotating generators, most multifunctional inverters installed in mini-grids do not have the capacity to generate these currents, thus being unable to black start the grid.

It should also be noted that the speed of the transfer relays used when the power plant switches from supplying the grid via the diesel generator (or other back-up source) to supplying the grid via the multifunctional inverter(s) is insufficient to prevent the demagnetization of the transformers. Thus, starting-up the diesel generator set and then switching back to the multifunctional inverter(s) does not guarantee the operation of the power plant.

Several solutions can be envisioned (gradual start-up of the grid, oversizing of the multifunctional inverter(s), etc.), but in all cases a detailed engineering phase that involves the inverter manufacturer and the transformer manufacturer is essential, and shall be supervised by the project manager.

2 NORMATIVE REFERENCES

The following normative documents contain provisions which, through reference in this text, constitute provisions of this guide. All normative documents are subject to revision and, since any reference to a normative document is deemed to be a reference to the latest edition of that document, parties to agreements based on this guide are encouraged to take steps to ensure the use of the most recent editions of the normative documents indicated below. Information on currently valid national and international standards and specifications can be obtained from the appropriate national standards organization.

The following referenced documents are required in the application of this standard. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies :

AFSEC 50064-302: ed1 2024 : Guidelines for the Inspection of Photovoltaic Mini-Grids

IEC 61836: Solar Photovoltaic Energy Systems - Terms, Definitions and Symbols

IEC 60529: Degrees of protection provided by enclosures (IP Code)

IEC 60904-3: Photovoltaic devices - Part 3: Measurement principles for terrestrial photovoltaic (PV) solar devices with reference spectral irradiance data

IEC 62305-2: Protection against lightning - Part 2: Risk assessment

IEC 61427-1: Secondary cells and batteries for renewable energy storage - General requirements and methods of test - Part 1: Photovoltaic off-grid application

IEC 61427-2: Secondary cells and batteries for renewable energy storage - General requirements and methods of test - Part 2: On-grid applications

IEC 62619: Secondary cells and batteries containing alkaline or other non-acid electrolytes - Safety requirements for secondary lithium cells and batteries, for use in industrial applications

IEC 62133: Secondary cells and batteries containing alkaline or other non-acid electrolytes - Safety requirements for portable sealed secondary cells, and for batteries made from them, for use in portable applications

IEC 62485-1 / -2: Safety requirements for secondary batteries and battery installations

IEC 61960: Secondary cells and batteries containing alkaline or other non-acid electrolytes - Secondary lithium cells and batteries for portable applications

IEC 60034: Rotating electrical machines

IEC 60664-1: Insulation coordination for equipment within low-voltage supply systems - Part 1: Principles, requirements and tests

IEC 61000-4-5: Electromagnetic compatibility (EMC) - Part 4-5: Testing and measurement techniques - Surge immunity test

IEC 61215: Terrestrial photovoltaic (PV) modules - Design qualification and type approval

IEC 61730 -1 and 2: Photovoltaic (PV) module safety qualification

IEC TS 62804: Photovoltaic (PV) modules - Test methods for the detection of potential-induced degradation

IEC 61724 – 1 and -2 : Photovoltaic system performance

IEC 62852: Connectors for DC-application in photovoltaic systems - Safety requirements and tests

IEC 60245-4: Rubber insulated cables - Rated voltages up to and including 450/750 V - Part 4: Cords and flexible cables

IEC 60502: Power cables with extruded insulation and their accessories for rated voltages from 1 kV (Um = 1,2 kV) up to 30 kV (Um = 36 kV)

IEC 61439: Low-voltage switchgear and controlgear assemblies

IEC 60269-6: Low-voltage fuses - Part 6: Supplementary requirements for fuse-links for the protection of solar photovoltaic energy systems

IEC 60947: Low-voltage switchgear and controlgear

IEC 60947-2: Low-voltage switchgear and controlgear - Part 2: Circuit-breakers

IEC 61643-11: Low-voltage surge protective devices - Part 11: Surge protective devices connected to low-voltage power systems - Requirements and test methods

IEC 61643-12: Low-voltage surge protective devices - Part 12: Surge protective devices connected to low-voltage power systems - Selection and application principles

IEC 61643-31: Low-voltage surge protective devices - Part 31: Requirements and test methods for SPDs for photovoltaic installations

IEC 60364-7-712: Low voltage electrical installations - Part 7-712: Requirements for special installations or locations - Solar photovoltaic (PV) power supply systems

IEC 62548: Photovoltaic (PV) Arrays – Design Requirements

IEC 62930: Electric Cables For Photovoltaic Systems With A Voltage Rating of 1,5 KV DC

IEC 60332-3-10:2018: Tests On Electric And Optical Fibre Cables Under Fire Conditions - Part 3-10: Test For Vertical Flame Spread Of Vertically-Mounted Bunched Wires Or Cables - Apparatus:

IEC 61215: 1:2021 Standard | Terrestrial Photovoltaic (Pv) Modules - Design Qualification And Type Approval - Part 1: Test Requirements Ed.3:

IEC 61643-31:2018: Low-voltage surge protective devices - Part 31: Requirements and test methods for SPDs for photovoltaic installations

IEC 60364-7-712:2017: Low voltage electrical installations - Part 7-712: Requirements for special installations or locations - Solar photovoltaic (PV) power supply systems

IEC 60364-7-712:2017: Low voltage electrical installations - Part 7-712: Requirements for special installations or locations - Solar photovoltaic (PV) power supply systems

IEC 62446: part 1 and 2 Photovoltaic (PV) systems - Requirements for testing, documentation and maintenance

IEC 62930:2017: Standard | Electric cables for photovoltaic systems with a voltage rating of 1,5 kV DC

ISO 3046: Reciprocating internal combustion engines -- Performance

ISO 8528: Reciprocating internal combustion engine driven alternating current generating sets

IEC 62133-2: Secondary cells and batteries containing alkaline or other non-acid electrolytes – Safety requirements for portable sealed secondary cells, and for batteries made them, for use in portable applications-

IEC 62116: Utility-interactive photovoltaic inverters -Test procedure of islanding prevention measures:

IEC 62509: Photovoltaic (PV) systems - Requirements for testing, documentation and maintenance - Stationary batteries

IEC60227: Polyvinyl chloride insulated cables of rated voltages up to and including 450/750 V

IEC 60228: Conductors of insulated cables

IEC 61140: Protection against electric shock - Common aspects for installation and equipment

IEC 62109: Safety of power converters for use in photovoltaic power systems\

IEC 62477: Safety requirements for power electronic converter systems and equipment

IEC TR 63410: Decentralized electrical energy systems roadmap

IEC 60227-1:2024: Polyvinyl chloride insulated cables of rated voltages up to and including 450/750.

IEC 60228: Conductors of insulated cables: This standard specifies the construction and electrical properties of conductors used in insulated cables, ensuring their performance and safety.

IEC 62852:2014: applies to connectors for use in the d.c. circuits of photovoltaic systems according to class II of IEC 61140:2001 with rated voltages up to 1 500 V d.c. and rated currents up to 125 A per contact. It applies to connectors without breaking capacity but which might be engaged and disengaged under voltage.

IEEE 2030.10.2021: IEEE Standard for DC Microgrids for Rural and Remote Electricity Access Applications

3 TERMS AND DEFINITIONS

AC Bus
Interconnection point of the different AC sources which is connected to the multifunctional inverter assembly, the main AC voltage generator of the system.

Battery
Several battery cells or monobloc batteries connected in series and/or parallel and used as a source of voltage and electrical energy.

Battery Charger (charging of a battery)
operation during which a secondary cell or battery is supplied with electric energy from an external circuit which results in chemical changes within the cell and thus the storage of energy as chemical energy.

Battery cell
A set of electrodes and electrolyte constituting the basic unit of a battery.

BMS
Battery Management System. Device for electronically controlling the charging and discharging of a battery.

DC-BATT box
Enclosure representing the DC bus in which the battery, PV charge controller(s) and multifunctional inverter(s) are electrically connected, and where protective devices can be placed.

DC Bus
Interconnection point of the different DC sources (excluding the PV generator) connected to the battery, the main DC voltage generator of the system.

DC generator
Direct current generator, driven by an internal combustion engine and charging a battery.

DC (Power) Converter
electronic conversion from direct current to direct current at a different voltage

Equipotential bonding (EB)
Connection to the system's earthing system and to which all the metallic masses of the materials and equipment installed are connected.

Equipotential bonding conductor (PE)
Electrical conductor carrying fault currents in an electrical circuit. The PE conductor is usually connected to earth.

Guide
Document published by (ISO, IEC or AFSEC) giving rules, orientation, advice, or recommendations relating to international or regional standardization.

Hybrid power plant with storage
Autonomous electricity production plant with electrochemical storage consisting of a photovoltaic generator and a diesel generator.

I_{RM}
Maximum current that can pass through a photovoltaic module.

Keraunic level
Average number of days per year when thunder is heard in a given area.

MACB
Main AC Board. Enclosure representing the AC bus in which the inputs and outputs of the multifunctional inverter assembly, the PV inverter(s) and the diesel generator(s) are electrically connected, and where protective devices can be placed.

Micrograds
A microgrid is an independent system composed of distributed energy resources, which normally is connected to the main grid with a tie-line. Due to imbalance between supply and load a microgrid can either connect with main grid or operate independently.

Monobloc battery
battery with multiple separate but electrically connected cell compartments each of which is designed to house an assembly of electrodes, electrolyte, terminals or interconnections and possible separators.

MPPT
Maximum Power Point Tracking. A method and device for internal control of a PV inverter or PV charge controller which ensures that the PV generator is operating at its maximum power.

MPPT photovoltaic charge controller
Electronic device that controls the charge of the battery, using MPPT technology on the PV side.

Multifunctional inverter
A single component or set of components providing bi-directional conversion of electricity between the DC and AC buses, including the functions of a stand-alone inverter and battery charger.

PEN conductor
PE conductor in the case of a TN-C regime, where the neutral and PE conductors are connected together.

PV array cable
Cable connecting the DC-PV box to the conversion equipment (single MPPT).

PV array combiner box
Enclosure located upstream of the MPPT input of the PV charge controller where protective devices can be placed.

PV cell
The most elementary device that exhibits the photovoltaic effect, producing an electric potential difference by the absorption of photons.

PV generator, PV array
Set of PV sub-arrays connected in parallel to a conversion equipment associated with the same MPPT

PV inverter
Conversion equipment which injects the DC power produced by a PV generator into the AC grid, using MPPT technology on the PV side.

PV module
The smallest set of interconnected PV cells completely protected against the environment.

PV string
A circuit in which PV modules are connected in series to form assemblies that generate the specified output voltage.

PV string cable
Cable connecting the PV strings to the junction box.

PV string combiner box
Closed or protected enclosure in which all the PV strings of a PV sub-array are electrically connected and where protective devices can be placed.

PV sub-array
Integrated mechanical and electrical assembly of PV strings and other components to form a unit for the production of direct current electrical energy.

PV sub-array cable
Cable connecting the PV string combiner boxes to the DC-PV box.

Stand-alone PV power plant
Autonomous electricity production plant with electrochemical storage consisting of a photovoltaic generator but without back-up generators.

PV subfield
set of PV arrays connected in parallel

STC
Standard Test Conditions prescribed in IEC 60904-3 for PV cells and modules.

Type 1 SPD:
One-port permanently connected SPDs, except for watt-hour meter socket enclosures, intended for installation between the secondary of the service transformer and the line side of the service equipment overcurrent device, as well as the load side, including watt-hour meter socket enclosures and molded case SPDs intended to be installed without an external overcurrent protective device.

Type 2 SPD
Permanently connected SPDs intended for installation on the load side of the service equipment overcurrent device; including SPDs located at the branch panel and molded case SPDs.

NOTE: The Imax value is the maximum single discharge current represented by an 8/20 µs waveform that the SPD can support.

Type 3 SPD
Point of utilization SPDs, installed at a minimum conductor length of 10 meters from the electrical service panel to the point of utilization

NOTE: For example, cord connected, direct plug-in, receptacle type and SPDs installed at the utilization equipment being protected. The distance (10 meters) is exclusive of conductors that are provided with or used to attach SPDs

4 PLANNING AND DESIGN OF PV MINI GRID SYSTEMS

4.1 Site Selection

The success and efficiency of a PV mini-grid installation heavily depend on the careful selection of the site. Factors such as solar irradiation, terrain, trees/structures that could shade the PV modules, accessibility, proximity to load centers, and environmental considerations play crucial roles in determining the viability of a site for PV mini grid deployment.

Considerations for Site Selection

1. **Solar Irradiation:** Choose sites with high solar irradiation levels to maximize energy generation potential. Data on solar irradiation can be obtained from local meteorological agencies or solar resource assessment studies.

2. **Terrain:** Select a flat or gently sloping terrain to simplify installation and minimize shading effects on PV panels. Steep terrain may require additional engineering solutions and increase installation costs. Preferable the terrain must provide minimum pollution on the PV modules as it will affect the power generation and could require additional maintenance/cleaning of the PV modules.

3. **Accessibility:** Ensure easy access to the site for transportation of equipment, maintenance activities, and future expansions. Accessibility via roads or short trails is essential for successful project implementation.

4. **Proximity to Load Centers:** Select sites close to the target community or load centers to minimize transmission losses and distribution costs. Proximity facilitates efficient power delivery and enhances the economic viability of the project.

5. **Environmental Considerations:** Assess potential environmental impacts, such as land use conflicts, wildlife habitats, and cultural heritage sites. Ensure compliance with environmental regulations and engage with local communities to address concerns and mitigate negative impacts.

The following PV module standard abstracts is recommended to support site selection for PV mini grids:

IEC 61724-1: outlines terminology, equipment, and methods for performance monitoring and analysis of photovoltaic (PV) systems. It also serves as a basis for other standards which rely upon the data collected. This document defines classes of photovoltaic (PV) performance monitoring systems and serves as guidance for monitoring system choices. This second edition cancels and replaces the first edition, published in 2017.

The edition includes the following significant technical changes with respect to the previous edition:
- Monitoring of bifacial systems is introduced.
- Irradiance sensor requirements are updated.
- Soiling measurement is updated based on new technology.
- Class C monitoring systems are eliminated.

IEC TR 63410:2023, which is a Technical Report, aims to prepare a road map for categorizing Decentralized Electrical Energy Systems and identifying gaps in the existing standards relevant to Decentralized Electrical Energy Systems. The task of IEC Subcommittee 8B is to develop IEC publications enabling the development of secure, reliable and cost-effective systems with decentralized management for electrical energy supply, which are alternative, complementary or precursors to traditional large interconnected and highly centralized systems. This includes but is not limited to AC, DC, AC/DC hybrid decentralized electrical energy systems, such as distributed generation, distributed energy storage, dispatchable loads, virtual power plants and electrical energy systems having interaction with multiple types of distributed energy resources.

4.2 Community Engagement and Capacity Building for Solar PV Installations

Ensuring the success and sustainability of solar PV mini-grid projects requires more than just technical expertise; it demands a commitment to fostering local ownership, acceptance, and involvement. The AFSEC guidelines underscore the significance of engaging communities through comprehensive awareness campaigns, stakeholder involvement, and targeted capacity-building programs. Such inclusive strategies not only pave the way for socio-economic upliftment and energy equity but also instill a sense of environmental responsibility among local populations.

Key Strategies for Effective Community Engagement:

Establish Inclusive Advisory Committees: Creating platforms like public advisory or citizen committees invites community members to play an active role in the solar PV project. By involving diverse representatives – from local residents to building users – in the planning and decision-making processes, these committees ensure that the project genuinely reflects the community's needs and aspirations.

Conduct Awareness and Information Sessions: Regularly organized informational meetings help demystify solar technology for the community, addressing any concerns and highlighting the benefits of solar energy. This educational approach fosters a deeper understanding and acceptance of the project, laying the groundwork for a smoother implementation phase.

Leverage Local Leaders and Networks: Building strong relationships with community leaders, local NGOs, and civic groups is crucial for mobilizing support and resources. These alliances not only facilitate trust but also enable the project to leverage existing networks for broader community buy-in and engagement.

Implement Targeted Capacity Building: Tailored training programs that enhance the community's ability to maintain and manage the solar PV systems are essential. These initiatives empower residents with the skills needed for long-term project sustainability, fostering a sense of ownership and pride in the renewable energy initiative.

By prioritizing transparent communication, inclusive participation, and empowering education, solar PV installation projects can achieve more than just technical success. They can become catalysts for community development, energy access, and environmental stewardship. This holistic approach not only ensures the project's longevity but also maximizes its positive impact on the community.

4.3 System Sizing

Accurate system sizing is crucial for designing a PV mini-grid that meets the energy demands of the target community while ensuring optimal performance and reliability. Proper system sizing involves estimating the required capacity of solar panels, batteries, inverters, and other components based on factors such as energy demand, solar irradiation levels, load profiles, temperature, altitude, and system autonomy requirements.

Key Considerations for System Sizing

1. **Energy Demand Assessment:** Conduct a thorough assessment of the energy needs of the target community or load center. Consider factors such as household electricity consumption, productive uses of energy, and future growth projections.

2. **Solar Irradiation Levels:** Utilize solar irradiation data to estimate the energy generation potential of the site. Ensure accurate measurements or reliable solar resource assessment tools to determine the available solar energy for the PV system.

3. **Load Profiles:** Analyze the load profiles of the target community to understand the variation in energy demand throughout the day, week, and year. Consider peak loads, night-time consumption, and seasonal variations to size the PV mini-grid appropriately. A smart energy management system could be deployed to optimize the energy demand profiles.

4. **System Autonomy**: Determine the desired level of system autonomy based on factors such as grid availability, reliability, and cost considerations. Choose a suitable battery

capacity and backup generator (if applicable) to ensure uninterrupted power supply during periods of low solar generation or grid outages.

5. **Component Selection:** Select PV panels, batteries, inverters, and other system components with capacities that match the estimated energy demand and system requirements. Consider factors such as efficiency, reliability, lifecycle costs, and compatibility with the existing infrastructure.

4.4 Design Considerations

4.4.1 System Main Components

PV mini grids comprise several essential components that work together to generate, store, and distribute electricity to the target community. Understanding the functions and specifications of these components is crucial for designing and installing a reliable and efficient PV mini-grid system.

1. **Solar Panels:** (PV Modules) Select high-quality solar panels with appropriate specifications such as efficiency, power rating, and durability. Ensure compliance with relevant standards for photovoltaic modules, detailed in the related component specification section of this guide.

2. **Inverter:** Converts DC electricity generated by solar panels into AC electricity suitable for powering AC loads. Choose inverters with the required capacity, efficiency, and grid compatibility. Always refer to standards, detailed in the related component specification section of this guide. such as IEC 62116 for grid connection of energy systems via inverters and IEC 61683 for photovoltaic inverters.

3. **Battery Bank:** Stores excess energy generated during periods of high solar irradiation for use during low solar generation or night-time hours. Select batteries with appropriate capacity, voltage, and cycle life to meet the energy storage requirements of the PV mini-grid system. Consider standards, detailed in the related component specification section of this guide for lead-acid batteries for lithium-ion batteries.

4. **Charge Controller:** Regulates the charging and discharging of batteries to optimize their performance and lifespan. Choose charge controllers with features such as maximum power point tracking (MPPT), temperature compensation, and overcharge protection. Refer to standards, detailed in the related component specification section of this guide, such as IEC 62509 for charge controllers for photovoltaic systems.

5. **Wiring and Cables:** Connect various components of the PV mini-grid system to ensure efficient energy transfer and electrical safety. Use high-quality wiring and cables with appropriate sizes, insulation, and protection against environmental factors. Adhere to standards for conductors, cables and electrical installations of buildings detailed in the related section of this guide.

4.4.2 Functionality of the main components

This section summarizes the functionalities of the main components studied in this guide. Other minor components will be dealt with in subsequent sections.

PV GENERATOR/PV MODULES

The function of the PV generator is to produce electricity from the solar irradiance falling on its surface.

The PV generator consists of several PV arrays, each consisting of several PV sub-arrays connected in parallel, each consisting of several PV strings connected in parallel, each consisting of several PV modules connected in series.

In the case of a system with a single PV charge controller and/or PV inverter, consisting of a single MPPT, the PV array is composed of one or more sub-arrays connected in parallel and with the same orientation. The proper solar panel orientation for PV installations located north of the equator is facing true south. For PV installations located south of the equator, it will be the opposite, facing true north. This will provide the best orientation to allow the most exposure time to the sun and produce the most amount of electricity.

In practice, most systems consist of several PV charge controllers and/or PV inverters, each with several independent MPP trackers.

The result is an overall system with several MPPTs, to which a single PV sub-array is connected in each case. The independence of the different MPPTs allows different PV sub-arrays to be realized within the same PV generator.

If several PV sub-arrays are connected in parallel within a PV array, they must be identical in voltage (identical modules, same orientation and tilt).

If several PV modules are connected in series within a PV string, they must be identical in current (identical modules, same orientation and tilt). Shading must be avoided and the maximum voltage of the string must be within the specification of the MPPT.

In practice and in general, all PV modules within the same PV array must be identical in every respect: power, voltage, current, within a maximum tolerance of +/- 5%.

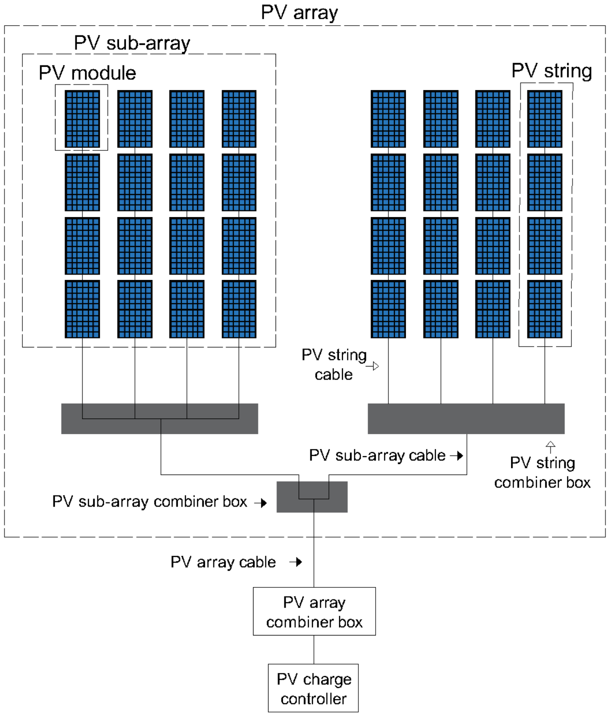


Figure 1: Example of a PV Array

NOTE: modern hybrid inverters have the capability with onboard MPPT'S to accommodate multiple PV array strings

If during the lifetime of the PV generator a PV module needs to be replaced, it shall be replaced by an identical module, or by a module with the following characteristics, compared to the other modules in service in the PV generator:

- Peak power shall be greater than or equal to the module being replaced.
- VOC and VMPP voltages at STC shall be equal to those of the replaced module, with a tolerance of +/- 5%.
- I_{MPP} current at STC shall be greater than or equal to that of the module being replaced

Technical specifications
The sections below show a non-exhaustive list of technical specifications whose level of requirement must be specified by the project engineer.

This information must be comprehensible and accessible in the technical documentation of the PV module.

Electrical characteristics
Performance under STC conditions (G= 1 kW/m²; AM 1.5; Tj= 25°C):

- Nominal power and tolerance (Wp)
- MPP voltage
- MPP current
- Open-circuit voltage
- Short-circuit current
- Nominal module efficiency.

Other parameters
- NOCT temperature (Nominal Operating Cell Temperature: G= 800 W/m²; AM 1.5; Ta= 20°C; wind = 1 m/s) and associated performance
- Temperature coefficient: power, voltage, current
- Maximum permissible PV string voltage
- Maximum permissible reverse current: IRM or fuse rating value.

General characteristics
- Operating temperature range
- Storage temperature
- Maximum static load
- Impact resistance
- Materials: front side, frame, rear side
- Number of cells
- Junction box
- Brand and reference of the pluggable PV connectors
- Number of bypass diodes
- Length of output cables, type and cross-section
- Dimensions (L x W x H)
- Weight
- Product and performance warranty
- Wrapping and packaging

Labelling
- Brand
- Model
- Type
- Serial number
- Peak power (according to IEC 61215)
- Uoc, Isc, Umpp, Impp
- Labelling of + and - terminals
- Class indications (IP, IK)
- Indications of compliance to standards
- Certification information

PV INVERTER

The PV inverter converts the DC electrical power from the PV generator into AC electrical power which is synchronized in voltage and frequency with the AC bus. It acts as a power generator and it automatically disconnects if there is no voltage source on the AC bus. PV inverters can have several MPPT inputs, each connected to an independent PV sub-array. Several PV inverters can be connected in parallel to the same AC bus.

Within a mini-grid, the PV inverter shall be able to adapt its power output depending on the frequency of the AC bus to which it is connected. This mode of communication between the mini-grid voltage source (in this guides case, the multifunctional inverters or electricity generator) and the PV inverters is the most common. However, care must be taken to ensure that the $P_{OND}=f(F_{HZ})$ curve linking the inverter power to the AC bus frequency is matched to the droop curve $F_{HZ}=f(P_{GE})$ of the genset, so that regulation can be effective when the mini-grid is supplied by the generator with direct injection of PV onto the AC bus.

If there is no communication integrated into the power plant via frequency shift or if the diesel generator droop curve is unsuitable, it is also possible to integrate an external control device which continuously measures the power demand from the grid and adapts the power injected by the PV inverters accordingly.

NOTE: PV inverters in high-power mini-grids can have nominal powers above 100 kW. Refer to the ECOSTAND standard "Minimum energy performance standards for mini-grid inverters in the ECOWAS region" for more information on high power inverters.

Multifunctional inverter (single component or assembly made from several components in a single design)

In principle the multifunctional inverter consists of a DC/AC inverter, an AC/DC rectifier and a transfer relay. The transfer relay can be sometimes installed separately, outside the inverter. The multifunctional inverter is the heart of the system, acting as the system's main AC voltage source. Among its various functions, it provides:

- The function of a permanent stand-alone inverter, by converting the electrical power of the DC bus into AC power to feed into the electrical grid,
- The function of a battery charger, by converting the electrical power received by the AC bus (via the diesel generator or PV inverter) into DC electrical power,
- The function of the transfer relay (internal or external to the unit), allowing the coupling of the external source (diesel generator) with the multifunctional inverter, after synchronization.
- Battery charge and discharge management
- Accommodating, when used, the PV arrays onto a managed DC busbar
- Many modern Inverters / Converters have remote access capability for monitoring or maintenance.

NOTE: Modern hybrid inverters have the capability with Onboard MPPT's to accommodate multiple PV array strings

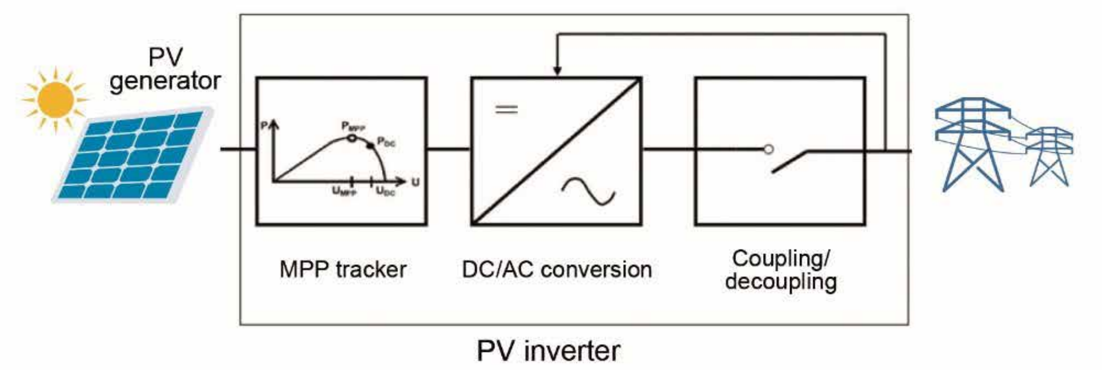


Figure 2: Schematic Diagram of a PV Inverter

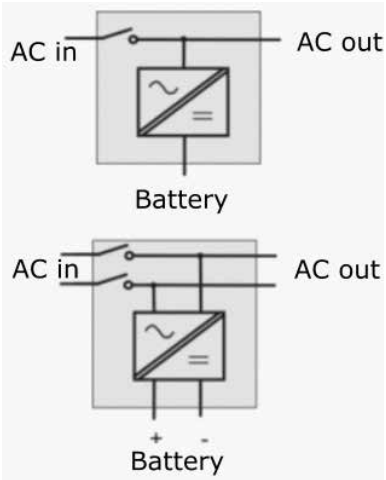


Figure 3: Schematic Diagram of a multifunctional inverter

NOTE: Multifunctional inverters in high-power mini-grids can have nominal powers in excess of 100 kW. Refer to the ECOSTAND standard "Minimum energy performance standards for mini-grid inverters in the ECOWAS region" for more information on high power inverters.

Recommended Standards

IEC 60146-1-1:2009 specifies the requirements for the performance of all semiconductor power converters and semiconductor power switches using controllable and/or non-controllable electronic valve devices. It is primarily intended to specify the basic requirements for converters in general and the requirements applicable to line commutated converters for conversion of a.c. power to d.c. power or vice versa. Parts of this standard are also applicable to other types of electronic power converter provided that they do not have their own product standards. This fourth edition constitutes a technical revision and introduces five main changes: - re-edition of the whole standard according to the current directives; - correction of definitions and addition of new terms, especially terms concerning EMC, harmonic distortion and insulation co-ordination; - the service condition tolerances have been revised according to the IEC 61000 series; - the insulation tests have been revised considering the insulation co-ordination; - addition of three annexes.

This part of IEC 61386 specifies requirements and tests for conduit systems, including conduits and conduit fittings, for the protection and management of insulated conductors and/or cables in electrical installations or in communication systems up to 1 000 V a.c. and/or 1 500 V d.c. This second edition cancels and replaces the first edition published in 1996, and its Amendment 1 (2000), and it constitutes a technical revision. The changes to the first edition are as follows: - change to the length of the test specimen between fittings for the tensile test, - editorial and normative reference updates.

EC 62909-1:2017 specifies general aspects of bi-directional grid-connected power converters (GCPC), consisting of a grid-side inverter with two or more types of DC-port interfaces on the application side with system voltages not exceeding 1 000 V AC or 1 500 V DC. In special cases, a GCPC will have only one DC-port interface, which is connected to a bidirectional energy-storage device. This document includes terminology, specifications, performance, safety, system architecture, and test-case definitions. The "system architecture" defines interaction between the inverter and converters. Requirements which are common, general, and independent of special characteristics of individual generators and bi-directional storages are defined. This document does not cover uninterruptible power supply (UPS) systems, which fall under the scope of IEC 62040 (all parts). Requirements for internal and external digital communication might be necessary; the interface requirements including communication with distributed energy resources are provided in a future part of IEC 62909. All EMC requirements are defined by reference to existing IEC standards. External communication requirements are out of scope of this document.

BATTERY

The electrochemical battery is a reversible generator which can store electrical energy in chemical form and then release it at any required time thanks to the reversibility of the transformation. These reactions are activated within an elementary cell (consisting of two electrodes immersed in an electrolyte) when a load is connected to its terminals via a managed connection.

The battery is connected to the DC bus and it is characterized by:

- Technology (Lead-acid, Li-ion, Cd-Ni, NIMH, etc.)

- The capacity expressed in Ah or kWh under a given discharge rate, a depth of discharge and temperature.

- Power density and energy density by mass,

- Cycling performance, which characterizes the service life and strongly depends on:
  - Technology,
  - Depth of Discharge (DoD) and discharge rates,
  - Duty cycles associated with DoD
  - The quality of the protections implemented against overloads and deep discharges,
  - The temperature of the electrolyte,

- The conversion efficiency in charge and discharge,

- The internal resistance, which characterizes the short-circuit current and therefore the nature of the electrical protections to be implemented on the DC bus.

In practice, the battery consists of several battery cells or monobloc batteries (unitary set of several cells connected in series, usually factory assembled) connected in series and/or parallel. The voltage and nominal capacity of the battery will depend on the characteristics of the individual cells and the electrical connection between each other.

Lead-acid technology is currently the predominant technology in the PV mini-grids covered in this guide. This technology currently offers the best techno-economic compromise and has a solid track-record.

At the same time, the market of lithium-based batteries, divided into several dozen technologies that can be summarized under the name "Li-Ion", is strongly growing and is gradually gaining marketplace in medium- and high-power PV plants with medium solar fraction. Unlike lead-acid batteries, Li-Ion batteries require a fine regulation of the charging cycles and are therefore systematically associated with a BMS (Battery Management System), which is commonly integrated into the battery and offered by the battery manufacturer. PV charge controllers and/or multi-functional inverters shall be compatible with the specific characteristics of the BMS.

Selection Criteria:

- **Capacity**: Determine the storage capacity of batteries based on energy demand, autonomy requirements, and expected periods of low solar generation.

- **Cycle Life**: Choose batteries with a high cycle life to withstand frequent charge-discharge cycles and prolong their operational lifespan.

- **Chemistry**: Consider the chemistry of batteries (e.g., lead-acid, lithium-ion) based on factors such as energy density, efficiency, and environmental considerations.

Batteries do contain hazardous chemicals and generate explosive gasses thus safe installations and charging regions is of paramount importance to ensure a safe installation

Characteristic	Lead-acid battery	Li-ion battery	Cd-Ni battery
Nominal voltage of a cell	2V	3.2 or 3.7 V	1,2V
Energy density by mass	25 to 45 Wh/kg	80 to 250 Wh/kg	20 to 60 Wh/kg
Energy density by volume	75-120 Wh/L	220-330 Wh/L	80-150 Wh/L
Self-discharge rate	< 5 %/month	5 to 10 %/month	20 %/month
Number of cycles @ 80% DoD Values depend on the manufacturer	Approx. 300 to 600 cycles for VRLA AGM up to 1200 cycles for batteries with positive tubular plates	Approx. 1500 to 5000 cycles	Approx. 1500 to 2000 cycles
Efficiency	70% to 90%	90% to 95%	60% to 80%
Operating temperature	from -20 to + 60°C	from -20 to + 50°C (0-60° for Li-Polymer)	from -40 to + 60°C
Experience	Mature technology with solid field experience	Mature technology for many portable applications.	Extensive feedback for portable applications.
Safety and environmental impacts	Common technology, regarded as safe. Imperative to recycle the batteries at least at an average of 65%. Toxic material	Stability issues (hence the high cost of the necessary protections). The recycling industry is gradually being stablished.	Cd is a highly toxic material

Table 1: Main characteristics of the different batteries

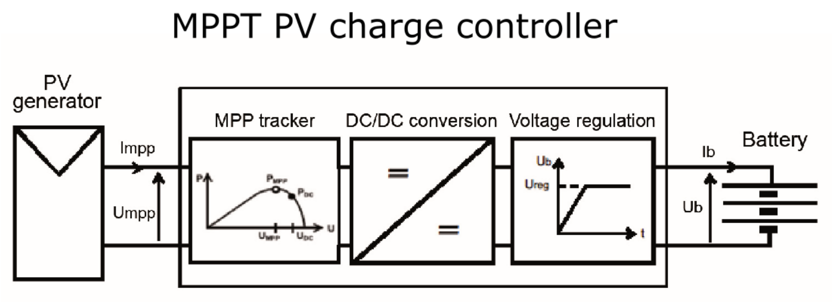


Figure 4: Schematic diagram of a MPPT PV charge controller

PHOTOVOLTAIC CHARGE CONTROLLER

The PV charge controller regulates the voltage from the PV generator to a voltage compatible with the battery. In view of recent technological developments and the range of application of this document, it is assumed that PV charge controllers have a MPPT functionality. Indeed, nowadays most manufacturers offer MPPT ranges from a few hundred Wp upwards. This technology is much more efficient than charge controllers with series, parallel or PWM technology, and offers a much greater wiring flexibility.

The PV charge controller ensures that the battery is charged in accordance with the manufacturer's specifications and for lithium batteries aligns with the battery management system (BMS). Charge controllers can have several MPPT inputs, each connected to an independent PV sub-array. Several charge controllers can be connected in parallel to the same DC bus.

WIRING AND CABLES

In practice, three criteria must be taken into account when sizing the cross-section of the cables between the various components of a system:

- the type of protection device and its current rating In
- the maximum admissible current of the cable, Iz, with a correction factor taking into account, if applicable, the ambient temperature, installation method, grouping of different circuits, etc.
- voltage drop induced by the cable's resistance, checking it against the permissible values.

4.5 Component Selection

Selecting the right components is crucial for the performance, reliability, and longevity of a PV mini-grid system. Each component, including solar panels, inverters, batteries, charge controllers, and wiring, plays a vital role in ensuring efficient energy generation, storage, and distribution.

SOLAR PANELS/MODULES

Selection Criteria:

- Efficiency: Choose solar panels with high efficiency to maximize energy generation from limited space.
- Power Rating: Consider the power rating of solar panels based on energy demand and available space.
- Durability: Consider panels with robust construction and weather-resistant materials to withstand harsh environmental conditions.

INVERTERS

Selection Criteria:

- Capacity: Select inverters with sufficient capacity to handle the maximum power output of the solar panels and meet peak load demand.
- Efficiency: Choose inverters with high efficiency to minimize energy losses during the conversion process.
- Grid Compatibility: Ensure inverters comply with grid connection standards and regulations applicable in the installation location.

BATTERIES – LEAD ACID

Recommendations, good practices and lessons learned regarding the choice of lead-acid batteries:

Depending on the application and the environmental and operating conditions, the battery type will be specified so that the investment and replacement costs are in line with the expected lifespan.

The choice of the battery type is not always easy to make as it has to take into account:

- Type of application
- Environmental conditions, especially the ambient temperature, which can be related to the space available in the technical room with the air volumes and ventilation devices necessary to evacuate the heat from the batteries.
- The presence or absence of staff capable of ensuring a proper maintenance protocol
- Local availability for purchase or replacement
- The available budget

In case of open batteries (liquid electrolyte) with positive tubular plates:

- For medium to high power applications
- Robust and not very sensitive to power surges
- Require regular full recharge cycles
- Can be delivered dry or with electrolyte and already formatted
- Require regular maintenance (maintenance of the electrolyte level by adding distilled water),
- Equalization charge preferably automatic at regular intervals (e.g., once a month).

Case of sealed batteries (AGM/gel electrolyte) with positive tubular plates:

- For medium to high power applications
- Slightly better theoretical cycling performance than open batteries
- Require precise, temperature-compensated charge regulation
- Sensitive to temperature and power surges
- Commissioning should not take place more than 12 to 18 months (depending on storage conditions) after the date of manufacture or the last complete refill.
- Maintenance-free
- More expensive than open batteries
- Reminder: sealed batteries must never be subjected to equalization charges.

Minimum requirements

The project engineer must define the project requirements based on the considerations presented in the previous sections and the specific context of the project. The normative references listed in Clause 2 and the minimum requirements presented in the following table must be respected in all projects.

Characteristic	Lead-acid battery
Energy density of the battery cell	≥ 20 Wh/kg (open batteries) ≥ 12 Wh/kg (sealed batteries)
Number of cycles @ 80% DoD and @20oC	≥ 1100 (open batteries and sealed batteries with gel electrolyte) ≥ 300 (AGM sealed batteries)
Operating temperature range	At least from 10° C to 45° C

Table 1: Minimum requirements for Lead-Acid Batteries

SERIAL AND PARALLEL CONNECTION OF SEVERAL BATTERIES

Example: implementation of a 500-kWh lead-acid battery - C20 rating.

Solution 1: three batteries in parallel, each consisting of 24 cells of 2 V - 3500 Ah - C20, i.e., a nominal voltage of 48 V.

> Very heavy battery cells (more than 200 kg in this example)
> Solution in the regime of ELV (U < 60 V), reducing the risks of electric shock and simplifying the protection to be implemented.
> Very high current flow in the DC bus (large cross-section cable together with switching and protection devices of high nominal currents)
> Redundant solution: service always available in case of failure of one of the 3 batteries
> Risk of imbalance between the 3 batteries and premature ageing.

Solution 2: Battery each consisting of 120 cells of 2 V - 2100 Ah - C20 rating, i.e., a nominal voltage of 240 V.

> Lighter battery cells
> Solution in the regime of LV (U > 60 V), involving specific measures for the protection of people:
  – Safety distance to avoid the simultaneous contact of the 2 terminals by an operator
  – Class II for all active conductors and accessible connectors
  – IP2X enclosure containing protections and switchgear (DC BATT box)
> Lower current through the DC bus
> Less reliable - Potential faulty system in case of failure of some battery cells.

BATTERIES – LI-ION

General considerations

- There are different types of Li-ion batteries classified by the type of alloy constituting the cathode (cobalt dioxide, iron phosphate, nickel-cobalt-aluminum oxide, polymer, etc...). The negative electrode is usually made of graphite. Nowadays LiFePO4 (LFP) batteries are considered the safest due to their superior chemical and thermal stability. They have a nominal cell voltage of 3.2V.

  A 12V battery is composed of 4 cells in series and has a nominal voltage of 12.8V. 12V, 24 and 48V batteries are increasingly used in small-scale grid-connected PV applications with storage or off-grid applications. However, research is still ongoing to ensure a long-term lifespan at high temperatures and increased safety.

- As of 2020, there is much less feedback from Li-ion PV mini-grids in the context of African rural electrification projects compared to the feedback from lead-acid PV mini-grids. Project engineers shall be careful when analyzing the performances offered by Li-ion batteries, which are usually marketed by the manufacturers themselves.

- Just as there are hundreds of different qualities of lead-acid batteries, there are also all types of so-called "Li-Ion" batteries on the market with widely varying performance, quality and fire risk.

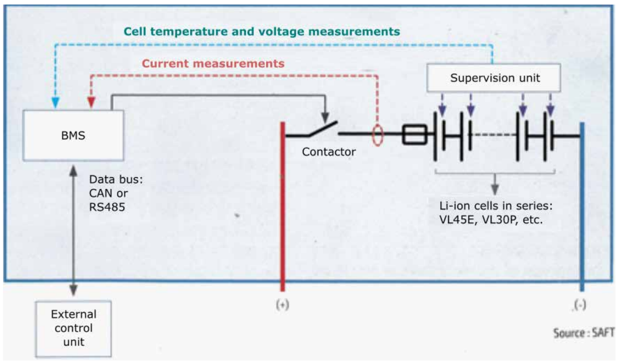


Figure 5: Architecture of a Li-Ion-battery

In practice, a high-capacity commercial Li-ion battery (non-portable applications) is composed of a set of components, supplied and assembled by a single manufacturer who is in charge of marketing, installation, configuration, and after-sales service:

- Battery cells and modules
- The BMS (Battery Management System)
- Thermal control
- Power components: fuses, contactors, current probes, power terminal block
- The mechanical casing of the whole ensemble.

Each cell is individually supervised by a control unit (part of the BMS) which performs the following functions:

- Voltage and current measurement
- Temperature measurement
- Cell balancing to optimize the lifespan
- Data transmission to the BMS
- Charge and discharge control
- Calculation of the state of charge (SoC)
- Monitoring of power devices
- Alarm management
- Communication with other external components or other same batteries when paralleled to increase capacity via data bus

CHARGE CONTROLLERS

Selection Criteria:

- Type: Select charge controllers (PWM or MPPT) based on system voltage, battery type, and efficiency requirements.
- Features: Look for features such as temperature compensation, overcharge protection, and load control to optimize battery performance and lifespan.
- Compatibility: Ensure compatibility between charge controllers and other system components such as solar panels and batteries.

WIRING AND CABLES

Selection Criteria of wiring:

- Size: Choose wiring and cables with appropriate sizes to minimize voltage drop and power losses.
- Insulation: Ensure wiring and cables have adequate insulation to withstand environmental conditions and prevent electrical hazards.
- Protection: Use protective measures such as conduit and junction boxes to safeguard wiring against physical damage and exposure to moisture.

PV CABLES

The rule for calculating the minimum cable cross-section is detailed in the ensemble of Table 52 (A,B,C,F,G,H,J,K,I,M,N,O,P,Q) of the NFC 15-100 standard.

To meet the severe ambient temperature conditions likely to be encountered in PV applications, unipolar double-insulated cables known as "solar" cables have been specially developed. Depending on the maximum core temperature (90°C or 120°C), the table on the right, in accordance with IEC 62930, specifies the maximum admissible current according to the cross-sections commonly used.

Type of cable	Cross-section (mm^2)	Max. admissible current (A) 2 cables on a wall (Ta = 30°C): I'z
Unipolar "solar" cable (Tmax= 90°C)	2,5 4 6 10	33 45 57 79
Unipolar "solar" cable (Tmax= 1200°C)	2,5 4 6 10	52 69 89 124

Table 3. Cross-section and maximum admissible current for each typ e of cable

EXAMPLE

Example 1: A PV string cable connected to PV modules delivering a current I_{sc} = 10 A must be able to withstand an operating current I_b = 1.25 I_{sc} = 12.5 A. According to the table above, this current can flow through a cable with a cross-section of 2.5 mm^2 or more.

Example 2: After the parallel connection of 4 identical PV strings as in example 1, the operating current is I_b = 4 x12.5 = 50 A. According to the table, the minimum conductor cross-section should be 6 mm^2 (if Tmax = 90°C) and 2.5 mm^2 (if Tmax = 120°).

NOTE: Be aware of the installation method and the voltage drop!

The examples mentioned here take into account only to the maximum admissible current of the cables for a given installation method and ambient temperature. Voltage drops are associated with the length of the cables. In some cases (long cable lengths), the cross-section selected may be compliant in terms of maximum admissible current, but insufficient when considering the voltage drop. On the other hand, for very short lengths (for example within the same technical room), voltage drops are often negligible and it is often necessary to prioritize the choice of cross-sections in terms of the maximum admissible currents and the method of installation.

4.6 Specifications and choice of components

Introduction

The purpose of this chapter is to collect the main general technical specifications and related standards (abstracts) recommended for the design of solar photovoltaic and/or hybrid power plant mini-grids.

Taking into account the specifications set out below allows to achieve the minimum technical recommendations, in particular in terms of safety and reliability, while repetition the expectations of users, particularly regarding the operating conditions of the equipment.

> The detailed design of a PV mini-grid requires a very good knowledge of both DC and AC electrical rules. Depending on the scope of the electrification project, it is up to the project developer to call upon a specialized design expert/consultant firm which will be responsible for writing up the technical specifications adapted to the local context.

PV GENERATOR

PV module

Technical specifications
The sections below show a non-exhaustive list of technical specifications whose level of requirement must be specified by the project engineer.

This information must be comprehensible and accessible in the technical documentation of the PV module.

Electrical characteristics
Performance under STC conditions (G= 1 kW/m²; AM 1.5; Tj= 25°C) :

- Nominal power and tolerance (Wp)
- MPP voltage
- MPP current
- Open-circuit voltage
- Short-circuit current
- Nominal module efficiency.

Current-Voltage Characteristics (I-V Curve)
In comparison with the common electrical installations, photovoltaic installations have specific characteristics that must be taken into account:

The current-voltage characteristics (I-V curves) of photovoltaic (PV) devices in natural or simulated sunlight measured in accordance with IEC 60904-1, provides a standardized basis for evaluating, assessing, optimizing, and monitoring the performance of PV modules and systems, contributing to the efficient and reliable generation of solar electricity.

During the day, under the effect of solar radiation, a DC voltage is generated by the PV generator. Interrupting the current from the PV generator does not eliminate this generated DC voltage.

In the event of a short circuit at the output of the PV generator, the current (ISC) is slightly higher than the current in normal operation (IMPP). Therefore, this characteristic specific to PV cells (which work as current sources) does not allow conventional protection equipment (fuses, circuit breakers) to be used for overcurrent protection. The difference between the value of the operating current IMPP and the short-circuit current ISC is too small if conventional protection devices were to be used. In addition, short-circuiting a PV module or PV array does not pose any functional problem to the modules.

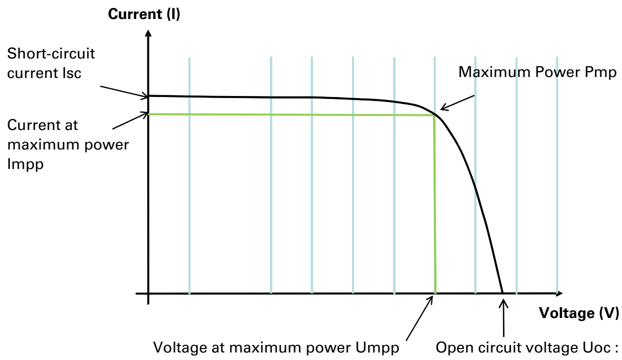


Figure 7: I-V curve of a PV generator

For PV generators with an open-circuit voltage Uoc of several tens of volts, arcing, which is difficult to interrupt, is likely to occur if the load circuit is opened or if there are contact faults. Two types of arcs are possible: series arcs and parallel arcs.

Series-type arcs occur under the following conditions:

- Opening of a photovoltaic circuit under load
- Contact fault

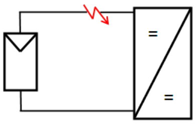


Figure 8: Series arc

Parallel arcs occur under the following conditions:

- Accidental opening of a short-circuited photovoltaic circuit
- Double insulation fault in an un-earthed PV generator
- Single insulation fault in an earthed PV generator

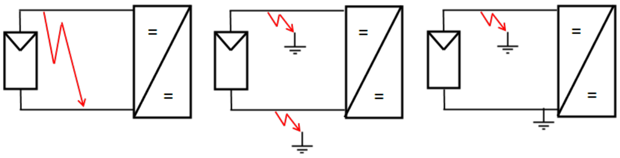


Figure 9: Parallel arc

However, arcing can only take place if certain conditions, both in terms of voltage and current, are met (in practice, arcing is possible when Uoc x Isc ≥ 120 W).

NOTE: Case of a PV generator with one polarity connected to earth

In general, most photovoltaic systems do not require earthing of one DC polarity.

However, for functional reasons, some PV module technologies require this type of earthing. As this type of technology is only rarely used in the PV mini-grids discussed in this guide, where crystalline silicon technology largely predominates, these applications are not discussed in this document

Other parameters

- NOCT temperature (Nominal Operating Cell Temperature: G= 800 W/m²; AM 1.5; Ta= 20°C; wind = 1 m/s) and associated performance
- Temperature coefficient: power, voltage, current
- Maximum permissible PV string voltage
- Maximum permissible reverse current: IRM or fuse rating value.

General characteristics

- Operating temperature range
- Storage temperature
- Maximum static load
- Impact resistance
- Materials: front side, frame, rear side
- Number of cells
- Junction box
- Brand and reference of the pluggable PV connectors
- Number of bypass diodes
- Length of output cables, type and cross-section
- Dimensions (L x W x H)
- Weight
- Product and performance warranty
- Wrapping and packaging

Labelling

- Brand
- Model
- Type
- Serial number
- Peak power (according to IEC 61215)
- Uoc, Isc, Umpp, Impp
- Labelling of + and - terminals
- Class indications (IP, IK)
- Indications of compliance to standards
- Certification info

Photovoltaic modules should comply with the following standards:

IEC 61215-1:2021 lays down requirements for the design qualification of terrestrial photovoltaic modules suitable for long-term operation in open-air climates. The useful service life of modules so qualified will depend on their design, their environment and the conditions under which they are operated. Test results are not construed as a quantitative prediction of module lifetime. This document is intended to apply to all terrestrial flat plate module materials such as crystalline silicon module types as well as thin-film modules. It does not apply to systems that are not long-term applications, such as flexible modules installed in awnings or tenting. This second edition of IEC 61215-1 cancels and replaces the first edition of IEC 61215-1, published in 2016. This edition includes the following significant technical changes with respect to the previous edition:

a. Addition of a test taken from IEC TS 62782.

b. Addition of a test taken from IEC TS 62804-1.

c. Addition of test methods required for flexible modules. This includes the addition of the bending test (MQT 22).

d. Addition of definitions, references and instructions on how to perform the IEC 61215 design qualification and type approval on bifacial PV modules.

e. Clarification of the requirements related to power output measurements.

f. Addition of weights to junction box during 200 thermal cycles.

g. Requirement that retesting be performed according to IEC TS 62915.

h. Removal of the nominal module operating test (NMOT), and associated test of performance at NMOT, from the IEC 61215 series.

EC 61730-1:2023 specifies and describes the fundamental construction requirements for photovoltaic (PV) modules in order to provide safe electrical and mechanical operation. Specific topics are provided to assess the prevention of electrical shock, fire hazards, and personal injury due to mechanical and environmental stresses. This document pertains to the particular requirements of construction. IEC 61730-2 defines the requirements for testing. Modules with modified construction are qualified as described in IEC TS 62915.

This document lays down requirements for terrestrial PV modules suitable for long-term operation in open-air climates with 98th percentile module operating temperatures of 70 °C or less. Guidelines for modules to be used at higher operating temperatures are described in IEC TS 63126.

This document is intended to apply to all terrestrial flat plate module materials, such as crystalline silicon module types as well as thin-film modules.

This document defines the basic requirements for various applications of PV modules, but it cannot be considered to encompass all national or regional codes.

IEC TS 61724-2 defines a procedure for measuring and analyzing the power production of a specific photovoltaic system with the goal of evaluating the quality of the PV system performance. The test is intended to be applied during a relatively short time period (a few relatively sunny days). The intent of this document is to specify a framework procedure for comparing the measured power produced against the expected power from a PV system on relatively sunny days.

EC TS 62804-1:2015(E) defines procedures to test and evaluate the durability of crystalline silicon photovoltaic (PV) modules to the effects of short-term high-voltage stress including potential-induced degradation (PID). Two test methods are defined that do not inherently produce equivalent results. They are given as screening tests; neither test includes all the factors existing in the natural environment that can affect the PID rate. The methods describe how to achieve a constant stress level. The testing in this Technical Specification is designed for crystalline silicon PV modules with one or two glass surfaces, silicon cells having passivating dielectric layers, for degradation mechanisms involving mobile ions influencing the electric field over the silicon semiconductor, or electronically interacting with the silicon semiconductor itself.

IEC 61140:2016 applies to the protection of persons and livestock against electric shock. The intent is to give fundamental principles and requirements which are common to electrical installations, systems and equipment or necessary for their coordination, without limitations with regard to the magnitude of the voltage or current, or the type of current, and for frequencies up to 1 000 Hz. It has the status of a basic safety publication in accordance with IEC Guide 104. This fourth edition cancels and replaces the third edition published in 2001 and Amendment 1:2004. This edition constitutes a technical revision.

In accordance with **IEC 61730-1 and IEC 61730-2**:

PV modules integrated in a PV generator supplying a voltage ≥120 V must comply with the requirements of application Class A (considered to meet the requirements of Class II).

A PV module with accessible conductive parts that form the frame or mounting system must have provisions for earthing, including identification via an appropriate earthing symbol.

All the modules forming the PV generator must have identical characteristics with the lowest possible tolerance (+/- 3 to 5%) on the nominal peak power.

In accordance with standard **IEC 61215: 1:2021 standard. – terrestrial photovoltaic (PV) modules – design qualifications and type approval - Part 1**: test requirement's ed.3, the maximum operating voltage must be clearly specified in the technical documentation and on the label on the back of the module. It must be compatible with the voltage levels present in the PV generator.

The value of the maximum reverse current IRM of the PV modules must be specified.

Typical warranties

Manufacturers typically offer product warranties of 5 to 10 years, and sometimes up to 12 to 20 years.

All PV module manufacturers offer a 20–30year performance warranty.

The manufacturers also provide with the PV modules' maximum annual power loss, and therefore of the PV generator.

NOTE: In both cases, the terms and conditions of the warranties are complex and specific to each manufacturer, particularly if there is no commercial entity of the manufacturer present in the country of installation.

In practice, the observed lifetimes of PV modules that comply with the standards and are implemented under optimum conditions are 20 to 30 years.

Recommendations
Recommendations, best practices and lessons learned regarding the choice of PV modules:

- Beware of the presence on the market of PV modules of dubious quality with no standards or warranties and whose labels are fancy and marketed at low prices by unscrupulous sellers.
- Beware of false certificates of conformity to IEC standards (certificates of origin may be required by the project owner).
- Some PV modules feature a black frame and black backsheet (the so-called "full black" modules). They offer an aesthetic advantage but they have a less efficient thermal behavior compared to conventional modules with aluminum frame and white backsheet.
- The new "mono-PERC" technologies offer a better performance at high temperatures.
- In difficult environments (humidity, saline environment, strong winds), the use of double-glass modules is recommended (better resistance over time to extreme climatic constraints).
- A "flash list" of all PV modules purchased for a certain project can be requested from the manufacturer, summarizing the detailed electrical characteristics of each PV module.

Specific recommendations regarding PV modules' soiling
The contexts encountered in the ECOWAS region may have a significant impact on the soiling of PV modules:

- Sand, dust, long dry seasons, sometimes associated with strong wind episodes
- High humidity, moss and mold in the rainy season
- Limited water availability on site
- Low tilt of the PV generators

As a reminder, the soiling of PV modules can have important consequences:

- Decrease in yield, especially in the case of "uniform" soiling, e.g., due to dust.
- The appearance of hot spots in the case of unevenly distributed soiling on a PV module (e.g., moss on a part of the cells). In addition to a yield decrease, the presence of hot spots over long periods of time and under strong sunlight can cause irreversible damage to the PV module.

Therefore, in addition to the recommendations for regular cleaning with clear water (no detergents, soap or other products with a non-neutral pH index), some PV module manufacturers also recommend surface treatments that limit dirt deposits, while guaranteeing better "self-cleaning" by rain.

Project engineers can therefore, in specific cases, require such specifications on the front glass of the PV modules.

Minimum requirements
The project engineer must define the project requirements based on the considerations presented in the previous sections and on the specific context of the project. The normative references listed and the minimum requirements presented in the following table must be respected in all projects.

Nominal efficiency at STC	≥ 13% (c-Si) ≥ 7% (thin-film)
Temperature coefficient of the nominal power	-0.5 %/°C or better
Operating temperature range	At least from 10°C to 60°C
Junction box IP rating	≥ IP65

Table 5: Minimum requirements of the PV module

PV MOUNTING STRUCTURE

Technical specifications

The sections below present a non-exhaustive list of technical specifications whose level of requirement must be specified by the project engineer. This information must be comprehensible and accessible in the technical documentation of the PT mounting structure.

Mechanical characteristics

- Appropriate material for the structure
- Type of mounting of the PV modules
- Material of the screws
- Anti-theft devices
- Tilt

In case of a tilted roof (metal sheet or steel tray type)

- Type of fixture to the roof
- Type of waterproofing at the anchoring points
- Ventilation space underneath the PV modules
- Tear-off calculation note

In the case of ground-mounted (or on a flat roof)

- Type of fixing for the anchoring to ground
- Top and bottom height of the structure measured from the ground level
- Possible device to prevent birds from staying on top of the structure
- Type of ground anchoring (on piles, studs, ground screws, concrete foundations, ballasts)
- Possible fencing:
  - Material
  - Height
  - Door
  - Locking device

Information to be provided by the manufacturer

- Nomenclature and detailed packaging
- Assembly instruction manual
- Calculation notes
- Dimensions
- Weight

PV mounting structures characteristics.
There is normative reference for PV mounting structures as such. It strongly depends on the building codes specific to each country, for which the climatic, wind and seismic conditions are different for PV on roof.

Ground mounted PV structures also need to be designed taking into considering the ground conditions and wind loading.

In practice, the PV structure manufacturer must systematically provide a detailed calculation note during the execution phase, specifying:

- The calculation tool or software
- The standards used for the design of the profiles
- The wind loads considered
- The type of soil
- The dimensions and specifications of the anchoring systems

A soil study characterizing its geophysical behavior may also be imperative.

Recommendations, good practices and lessons learned regarding the choice of PV mounting structures:

- In humid and/or saline environments, aluminum, stainless steel and treated wood profiles are preferred over painted or galvanized steel profiles.

- Beware of electrolytic couples when two different metals are in contact (e.g. copper/aluminum or aluminum/steel). In saline and humid environments, PV modules (aluminum frame) should be placed on aluminum rails and the fixing clamps shall be made of aluminum (especially if the earthing is supposed to be ensured by the metal contacts). Washers made of synthetic materials can be considered to avoid the contact between two different metals.

- The stainless steel/aluminum couple is lightly corrosive. An ideal compromise for a PV structure is to have the aluminum profiles and all the screws and bolts made of grade 316 stainless steel (15 to 20 years life span).

- In a vegetated area, it is preferred to have the lowest point of the PV module at a height greater than 80 cm from the ground, to limit the risk of shading.

- Beware of thermal expansion in case of strong temperature variations, especially if several types of metals are distributed along the structure.

- Anti-theft devices should be provided. Several solutions are possible:

  – Tamper-proof screws (complex head or hammer head)
  – Modules installed in a welded structure
  – Electronic device integrated in the PV module's junction box, making it inactive in case of disconnection of the PV generator.
  – Presence of a security guard on site

- A robust fence around the PV generator is essential. Galvanized steel metal fences with a height of more than 1.5 m are preferred.

Minimum requirements
The project engineer must define the project requirements based on the considerations presented in the previous sections and the specific context of the project. The normative references listed in this guide and the minimum requirements presented in the following table must be respected in all projects.

Height of the lowest point, vegetated area	≥ 80 cm

Table 6: Minimum requirements of the PV mounting structure

COMPONENTS FOR THE CONVERSION, STORAGE AND MANAGEMENT OF ELECTRICAL ENERGY

MPPT PV CHARGE CONTROLLER

Technical specifications

The charge controller is one of the essential components to guarantee a minimum battery lifetime: the charge control prevents permanent overcharging of the battery while ensuring sufficient recharging.

The characteristics of the charge controller must be compatible with the type of battery selected (open lead-acid, sealed lead-acid, Li-ion, other).

The sections below present a non-exhaustive list of technical specifications whose level of requirement must be specified by the project engineer. This information must be comprehensible and accessible in the technical documentation of the charge controller.

Electrical characteristics:

Characteristics under load

- Nominal voltage
- Nominal charging current
- Max. charge current
- MPPT regulation
- Regulation phases according to the battery technology. An example for lead-acid batteries:
  - Bulk phase
  - Absorption phase
  - Floating phase
  - Equalization phase (only for open lead-acid batteries)
  - Type of activation and period of the equalization charge: automatic and/or manual
- Typical values of charging thresholds and tolerances
- Possible adjustment of thresholds and average values
- Temperature compensation and correction coefficient
- No-load consumption
- Efficiency
- Description of the functional status of the controller (LEDs, display)
- Protection against reverse polarity and parasitic overvoltage's
- Internal or external monitoring device

Protective devices

- Limited output voltage in case of battery disconnection and presence of PV generator
- Reverse polarity protection of the PV generator or battery
- Protection against transient overvoltage
- Electronic protection against overloads at both input and output
- Protection against over-temperature
- Protection against reverse currents (from battery to PV generator)

General characteristics:

- Adapted to specific climatic conditions
- IP rating
- Type of connections and current capacity of the connectors
- Operating status display: light indicators, digital display.
- Communication interface
- Operating temperature range
- Storage temperature range
- Dimensions (L x W x H)
- Weight
- Warranty

Labelling:

- Brand
- Model
- Type
- Serial number
- Nominal voltage
- Maximum permissible current
- Maximum permissible voltage
- MPPT operating voltage (optimum range)
- Minimum operating voltage
- Voltage thresholds for the specific battery type
- Marking of the + and - terminals at the PV input, the battery connection and the output to the loads
- Safety instructions
- Indications of conformity to standards
- Certification information

PV charge controllers should comply with the following standards:

IEC 62509:2010 establishes minimum requirements for the functioning and performance of battery charge controllers (BCC) used with lead acid batteries in terrestrial photovoltaic systems. The main aims are to ensure BCC reliability and to maximise the life of the battery.

EC 62477-1:2022 applies to power electronic converter systems (PECS), any specified accessories, and their components for electronic power conversion and electronic power switching, including the means for their control, protection, monitoring and measurement, such as with the main purpose of converting electric power, with rated system voltages not exceeding 1 000 V AC or 1 500 V DC.

This document also applies to PECS which intentionally emit or receive radio waves for the purpose of radio communication.

This document can also be used as a reference standard for product committees producing product standards for:

- adjustable speed electric power drive systems (PDS);
- standalone uninterruptible power systems (UPS);
- low voltage stabilized DC power supplies;
- bidirectional power converters.

For PECS and their specified accessories for which no product standard exists, this document provides minimum requirements for safety aspects.

This document has the status of a group safety publication in accordance with IEC Guide 104 for power electronic converter systems for solar, wind, tidal, wave, fuel cell or similar energy sources.

According to IEC Guide 104, one of the responsibilities of technical committees is, wherever applicable, to make use of basic safety publications and/or group safety publications in the preparation of their product standards.

Guidance for use of this group safety publication for product committees is given in Annex E.

This document
- establishes a common terminology for safety aspects relating to PECS,
- establishes minimum requirements for the coordination of safety aspects of interrelated parts within a PECS,
- establishes a common basis for minimum safety requirements for the PECS portion of products that contain PECS,
- specifies requirements to reduce risks of fire, electric shock, thermal, energy and mechanical hazards, during use and operation and, where specifically stated, during service and maintenance, and
- specifies minimum requirements to reduce risks with respect to PECS designed as pluggable and permanently connected equipment, whether it consists of a system of interconnected units or independent units, subject to installing, operating and maintaining the PECS in the manner prescribed by the manufacturer.

This document does not cover:
- telecommunications apparatus other than power supplies to such apparatus,
- functional safety aspects as covered by, for example, IEC 61508 (all parts), and
- electrical equipment and systems for railways applications and electric vehicles.

EC 62109-1:2010 applies to the power conversion equipment (PCE) for use in photovoltaic systems where a uniform technical level with respect to safety is necessary. It defines the minimum requirements for the design and manufacture of PCE for protection against electric shock, energy, fire, mechanical and other hazards. Provides general requirements applicable to all types of PV PCE.

Typical warranties usually cover 2 to 5 years. The service life of the equipment varies from 3 to 10 years under normal operating conditions.

Preference will be given to equipment with a permanent sales representation in the country of installation to facilitate maintenance, after-sales service and a possible warranty replacement.

Recommendations, good practices and lessons learned regarding the choice of charge controllers:

- If a sealed lead-acid battery is used, it must be ensured that the controller can inhibit the "equalization charge" function, or that it can only be accessed by setting the parameters in "Expert" mode.
- The charging thresholds must be adjustable and temperature-compensated.
- MPPT charge controllers with galvanic isolation simplify the implementation of personal and equipment protection by avoiding reverse currents from the DC bus to the PV bus and vice versa.
- In the case of Li-Ion batteries, the BMS manufacturer of the battery and the manufacturer of the charge controller must certify the compatibility of the equipment and provide all the necessary indications for the configuration of the charge controller.
- In order to lengthen the service life, it is recommended to slightly oversize the charge controller so that it does not work at the limit of its capacity under a high irradiance (and also high temperature).
- Charge controllers with multiple MPPT inputs offer greater flexibility in use and sizing.
- Make sure that the communication bus is compatible with all other equipment (multifunctional inverter, PV inverter, etc.).

Minimum requirements

The project engineer must define the project requirements based on the considerations presented in the previous sections and the specific context of the project. The normative references listed in Section 6.3.1.2 and the minimum requirements presented in the following table must be respected in all projects.

Regulation phases for lead-acid batteries	"Bulk", "absorption", "floating" and "equalization".
Maximum efficiency	≥ 95%
Operating temperature range	At least from 10°C to 50°C
IP rating	≥ IP20

Table 7: Minimum requirements of the MPPT PV charge controller.

PV INVERTER/HYBRID PV INVERTER

Technical specifications
In PV mini-grids with AC-coupled PV generators (or both AC- and DC- coupled PV generators), the PV generator is connected to the AC grid via a PV inverter (PCE).

NOTE: Inverters can be single of three phase units.

The sections below show a non-exhaustive list of technical specifications whose level of requirement must be specified by the project engineer. This information must be comprehensible and accessible in the technical documentation of the PV inverter.

Electrical characteristics:
DC input at 25°C

- Recommended PV generator power range
- MPPT voltage and power range
- Minimum voltage
- Maximum voltage
- Maximum current
- Minimum current
- Number of independent MPPT inputs
- Number of input connections per MPPT input and current carrying capacity

AC connection at 25°C
- Nominal inverter power rating
- For hybrid inverter, the maximum load supply power rating
- For hybrid inverter is there more than one load supply e.g. essential load and non-essential load
- Output power (5s at 25°C)
- Output power (30 min. at 25°C)
- Nominal voltage
- Voltage range and tolerance
- Single or three phase output
- Nominal frequency and tolerance
- Maximum output current continues
- Maximum output current for short duration.
- Power factor
- Maximum efficiency values and at different power values: P=100% Pn, P=50% Pn, P=20% Pn, P=5% Pn
- Power regulation curve as a function of the AC frequency
- Ability to generate reactive power
- Harmonic distortion on the current

Protection
- Earth fault
- Protection against reverse polarity in DC
- Short-circuit behavior on the AC side
- Insulation fault
- Anti-islanding
- IP rating
- for hybrid inverter, overcurrent protection shut down

General characteristics:
- Topology (low-frequency transformer, high-frequency transformer, transformerless)
- Cooling method
- Operating temperature range
- No-load / night- consumption
- Operating temperature
- Relative humidity
- IP ratings
- Noise level in db
- Communication interface
- Wi-fi remote access capability
- Internal or external monitoring
- Display
- Type of DC/MPPT and AC connections
- Parallel (or master-slave) capability
- Dimensions (L x W x H)
- Weight kg
- Warranty
- Mounting type

Labelling:
- Brand
- Model
- Type
- Serial number
- Permissible input DC voltage range
- Permissible input power at 25°C
- Nominal output AC voltage
- Maximum output power at 25°C
- Marking of the + and - terminals at the DC input
- Certification info

PV inverters should comply with the following standards::

IEC 62116:2014 provides a test procedure to evaluate the performance of islanding prevention measures used with utility-interconnected PV systems. This standard describes a guideline for testing the performance of automatic islanding prevention measures installed in or with single or multi-phase utility interactive PV inverters connected to the utility grid. The test procedure and criteria described are minimum requirements that will allow repeatability. Major changes with respect to the previous edition concern the DC power source and test condition.

IEC 62109-1:2010 applies to the power conversion equipment (PCE) for use in photovoltaic systems where a uniform technical level with respect to safety is necessary. Defines the minimum requirements for the design and manufacture of PCE for protection against electric shock, energy, fire, mechanical and other hazards. Provides general requirements applicable to all types of PV PCE.

EC 62109-2:2011 covers the particular safety requirements relevant to d.c. to a.c. inverter products as well as products that have or perform inverter functions in addition to other functions, where the inverter is intended for use in photovoltaic power systems. Inverters covered by this standard may be grid-interactive, stand-alone, or multiple mode inverters, may be supplied by single or multiple photovoltaic modules grouped in various array configurations, and may be intended for use in conjunction with batteries or other forms of energy storage. This standard must be used jointly with IEC 62109-1.

EC TR 61000-1-1:2023 which is a Technical Report, aims to describe and interpret various terms considered to be of basic importance to concepts and practical application in the design and evaluation of electromagnetically compatible equipment and systems. In addition, attention is drawn to the distinction between electromagnetic compatibility (EMC) tests carried out in a standardized set-up and those carried out at other locations, for example at premises where a device, equipment or system is manufactured or at the location where a device, equipment or system is installed (in situ tests or measurements). This second edition cancels and replaces the first edition published in 1992. This edition constitutes a technical revision. This edition includes the following significant technical changes with respect to the previous edition:

a. the general description of the electromagnetic environment has been updated in accordance with IEC TR 61000-2-5;

b. the description of source, of potentially susceptible equipment/systems and of coupling mechanism has been updated,

c. elements from IEC TR 61000-2-3, that is intended to be withdrawn, as well as from IEC TR 61000-2-5, have been incorporated into this document.

IEC 61508:2010 which covers those aspects to be considered when electrical/electronic/ programmable electronic (E/E/PE) systems are used to carry out safety functions. A major objective of this standard is to facilitate the development of product and application sector international standards by the technical committees responsible for the product or application sector. This will allow all the relevant factors, associated with the product or application, to be fully taken into account and thereby meet the specific needs of users of the product and the application sector. A second objective of this standard is to enable the development of E/E/PE safety-related systems where product or application sector international standards do not exist

IEC 62477, IEC 62477-1: Electronic Equipment for use in Power Installations (Abstract as covered under CC)

NOTE: Grid connection: Depends on the country of application- off grid configuration must be possible at the factory or on site.

Typical warranties
Product warranties are usually from 5 to 10 years, although extensions may be offered by manufacturers.

The service life of the equipment varies from 3 to 15 years under normal operating conditions.

Preference will be given to equipment with a permanent sales representation with an OEM relationship in the country of installation to facilitate maintenance, after-sales service and a possible warranty replacement.

Recommendations
Recommendations, best practices and lessons learned regarding the choice of PV inverters:

- In order to be able to charge the battery without risks, the total power of all PV inverters must be equal or less than the power of all multifunctional inverters. Some manufacturers offer their own recommendations for the sizing of PV inverters.

- Preference should be given to brands that are identical to the multifunctional inverter or for which the operation and adjustment in stand-alone (or "off-grid") mode is certified by both manufacturers.

- MPPT PV inverters with galvanic isolation simplify the implementation of personal and equipment protection by avoiding reverse currents from the AC bus to the PV generator and vice versa.

- Make sure that the communication bus is compatible with other equipment (multifunctional inverter, PV charge controller, etc.).

Minimum requirements
The project engineer must define the project requirements based on the considerations presented in the previous sections and the specific context of the project. The normative references must be respected in all projects.

MULTIFUNCTIONAL INVERTER

Technical specifications
Reminder: the multifunctional inverter can be a single unit or an assembly of several components integrated performing the same functions.

The sections below show a non-exhaustive list of technical specifications whose level of requirement should be specified by the project engineer. This information must be comprehensible and accessible in the technical documentation of the multifunctional inverter.

Electrical characteristics:
Functions
- AC input current limitation
- Assistance to the AC source
- Transfer relay capacity
- Parallel (or master-slave) and three-phase operation possible.

Inverter mode
- Nominal battery DC voltage
- Input AC voltage range
- Continuous output power at 25°C
- Output power (5s at 25°C)
- Output power (30 min. at 25°C)
- Temperature de-rating curve
- Rated output voltage and tolerance: single-phase or three-phase
- Output frequency and tolerance
- Output signal: sinusoidal or pseudo-sinusoidal
- Harmonic distortion
- Nominal output current
- Short-circuit current
- power factor
- Efficiency values. Maximum, and at different power values: P=100% Pn, P=50% Pn, P=20% Pn, P=5% Pn
- Presence of standby (Yes or No); if yes, indicate standby level value
- No-load, standby and self-consumptions
- Short circuit protection
- Overload protection
- Over-temperature protection
- Low voltage disconnection threshold (current-dependent thresholds, adjustments and compensations)
- Remote control ON / OFF
- Alarm contact (isolated relay contact)
- Galvanic insulation or not

Charger mode

- Nominal input AC voltage (single or three-phase)
- Input voltage range and tolerance
- Input frequency and tolerance
- Power factor
- Maximum charging current
- Current settings and average values
- Regulation phases according to the battery technology. Example for lead-acid battery as lithium battery managed by an internal battery management system (BMS):
  - Floating phase
  - Equalization phase (only for non-sealed type lead-acid batteries)
  - Type of activation of the equalization phase: automatic and/or manual
- Typical values of charging thresholds and tolerances, ability to adjust (or not) the threshold and average values
- Temperature compensation and correction coefficient
- Efficiency
- Signage of the charger's functional status (LEDs, display, ...)
- Short-circuit protection at the output
- Protection against an excessive battery voltage
- Protection against over-temperature
- Protection against reverse polarity and overvoltage's

Load management (for lead-acid batteries)

- Relay control or alarm based on the battery state of charge (SoC calculation and/or voltage reading)
- Automatic disconnection of loads before the battery is fully discharged

Multifunctional inverters should comply with the following standards:

Safety: IEC 60335-1:2020 deals with the safety of electrical appliances for household and similar purposes, their rated voltage being not more than 250 V for single-phase appliances and 480 V for other appliances including direct current (DC) supplied appliances and battery-operated appliances.

Appliances not intended for normal household use but which nevertheless may be a source of danger to the public, such as appliances intended to be used by laymen in shops, in light industry and on farms, are within the scope of this standard. This standard deals with the reasonably foreseeable hazards presented by appliances that are encountered by all persons.

Emission/Immunity: IEC TR 61000-1-1:2023 which is a Technical Report, aims to describe and interpret various terms considered to be of basic importance to concepts and practical application in the design and evaluation of electromagnetically compatible equipment and systems. In addition, attention is drawn to the distinction between electromagnetic compatibility (EMC) tests carried out in a standardized set-up and those carried out at other locations.

IEC 61558-1:2017 deals with safety aspects of transformers, reactors, power supply units and combinations thereof such as electrical, thermal and mechanical safety. This document covers the following independent or associated stationary or portable types of dry-type transformers, power supply units, including switch mode power supply units, reactors and combinations thereof in the field of safety.

IEC 61140:2016 applies to the protection of persons and livestock against electric shock. The intent is to give fundamental principles and requirements which are common to electrical installations, systems and equipment or necessary for their coordination, without limitations with regard to the magnitude of the voltage or current, or the type of current, and for frequencies up to 1 000 Hz. It has the status of a basic safety publication in accordance with IEC Guide 104. This fourth edition cancels and replaces the third edition published in 2001 and Amendment 1:2004. This edition constitutes a technical revision

General characteristics:

- Operating temperature range
- IP rating
- Cooling method
- Visible operational status
- Type of connections
- Auxiliary contacts
- Maximum transfer time
- Communication interface
- Noise level db
- dimensions (L x W x H) and Weight kg

Labelling:

- Brand
- Model
- Type
- Serial number
- Permissible input DC voltage range
- Nominal output AC voltage
- Nominal output power 25°C
- Marking of the + and - terminals at the input
- Certification info

Typical warranties

Product warranties are usually from 2 to 5 years, although extensions may be offered by manufacturers.

The service life of the equipment varies from 5 to 12 years under normal operating conditions.

Preference will be given to equipment with a permanent sales representation in the country of installation to facilitate maintenance, after-sales service and a possible warranty replacement.

Recommendations

Recommendations, good practices and lessons learned regarding the choice of multifunctional inverters:

- Different manufacturers of multifunctional converters can offer very different characteristics. It is very important to ensure that the device's functionalities are appropriate for the intended application, such as:
  - The possibility of limiting the input current (AC IN) to adapt external loads (PV inverter, diesel generator)
  - The ability to provide assistance to the source AC
  - The rating of the transfer relay
  - The number of devices that can be connected in series and parallel on the same AC bus

- Preference should be given to brands that are identical to the PV inverter (in the case of an AC-coupled system) or for which the PV inverter's stand-alone (or "off-grid") operation with the multifunctional inverter is certified by both manufacturers.

- Multifunctional inverters with galvanic isolation can simplify the implementation of protection of people and equipment by avoiding reverse currents from the AC bus to the DC bus and vice versa.

- Using Li-Ion batteries, the BMS manufacturer and the controller manufacturer must certify the compatibility of their equipment and provide all the necessary indications for the configuration of the controller.

- Perfect mastery of the operation of the multifunctional converter unit is essential to ensure its interoperability and optimal operation. A setting error can lead to major malfunctions and very rapid degradation of the battery.

- Make sure that the communication bus is compatible with other equipment (PV inverter, controller, etc.).

Minimum requirements

The project engineer must define the project requirements based on the considerations presented in the previous sections and the specific context of the project.

NOTE: The normative references listed in Clause 2 and the minimum requirements presented in the ECOSTAND standard "Minimum Energy Performance Standards for Mini-Grid Inverters in the ECOWAS region" must be respected in all projects in the ECOWAS region.

LEAD-ACID BATTERIES

Technical specifications

The sections below show a non-exhaustive list of technical specifications whose level of requirement must be specified by the project engineer. This information must be comprehensible and accessible in the technical documentation of the lead-acid battery.

Manufacturing characteristics:

- Alloy type and geometry of positive and negative plates
- VRLA/AGM (sometimes referenced as a sealed battery) or normal free electrolyte (open batteries) cell/battery
- Type of container (transparent or not)
- Type of cell ventilation plugs (explosion-proof or recombination plugs for open batteries)
- Ventilation requirements for open batteries
- Type of terminals
- Type of terminal cover
- Nominal electrolyte density for open batteries
- Date of manufactures commissioning charge for sealed batteries (AGM/gel)
- Manufactures commissioning charge date for open batteries delivered with liquid inside and maximum shelf life
- Dry charged battery cells manufactured date, maximum shelf life
- Recycling recommendations

Electrical characteristics at 25°C:

- Nominal voltage
- Expected life under normal operating conditions
- Nominal capacity Ah and/or kWh (at C10, C100 with minimum limit voltage)
- Monthly self-discharge rate
- Recommended charge and discharge regulation thresholds
- Energy efficiency
- Cycling performance (number of cycles) to a specific DOD (depth of discharge)
- Temperature-dependent compensation coefficients of the regulation thresholds

General characteristics:

- Operating temperature (min/max)
- Storage temperature
- Dimensions (L x W x H)
- Dry weight and electrolyte volume for open cells/batteries
- Total weight for sealed batteries

Labelling:

- Manufacturer's brand
- Battery type
- Date of manufacture or commissioning charge date for sealed batteries (AGM/gel)
- Manufactures commissioning charge date for open batteries delivered with liquid inside
- Nominal voltage
- Nominal capacities at C10 or C20 and C100 depending on the type of battery
- Nominal electrolyte density of the fully charged battery (for open batteries)
- Marking of maximum and minimum electrolyte levels (for open batteries)
- Marking of the + and - terminals
- Safety signs indicating hazards
- Indications of conformity to standards

Lead-acid batteries should comply with the following standards:

IEC 61427-1:2013 is part of a series which gives general information relating to the requirements for the secondary batteries used in photovoltaic energy systems (PVES) and to the typical methods of test used for the verification of battery performances. This part deals with cells and batteries used in photovoltaic off-grid applications. This standard is applicable to all types of secondary batteries.

IEC 61427-2:2015 relates to secondary batteries used in on-grid Electrical Energy Storage (EES) applications and provides the associated methods of test for the verification of their endurance, properties and electrical performance in such applications. The test methods are essentially battery chemistry neutral, i.e., applicable to all secondary battery types. On-grid applications are characterized by the fact that batteries are connected, via power conversion devices, to a regional or nation- or continent-wide electricity grid and act as instantaneous energy sources and sinks to stabilize the grids performance when randomly major amounts of electrical energy from renewable energy sources are fed into it. Related power conversion and interface equipment is not covered by this part of IEC 61427.

IEC 62133-1:2017 specifies requirements and tests for the safe operation of portable sealed secondary nickel cells and batteries containing alkaline electrolyte, under intended use and reasonably foreseeable misuse.

Typical warranties

Warranties usually offered are 1 or 2 years. Since lifetimes are extremely dependent on the conditions of use, it is not possible for manufacturers to offer extended warranties.

The service life of the batteries can vary from 3 to 15 years under normal operating conditions. The main parameters influencing the lifetime of a lead-acid battery are:

- The temperature of the electrolyte (liquid or gel/AGM)
- Number of cycles and depth of discharge (DOD)
- The quality of the charge regulation and deep-discharge protection
- Whether the recharge has been complete or not at each cycle
- Regular equalization at higher than float voltage for open batteries in order to avoid stratification of the electrolyte.
- Non-compliant battery storage prior to placing the battery in service

LI-ION BATTERIES

Technical specifications:
The following sections show a non-exhaustive list of technical specifications whose level of requirement must be specified by the project designer. This information must be comprehensible and accessible in the technical documentation of the Li-ion battery.

Manufacturing characteristics:
- Type of Li-ion technology
- Balancing technology between cells
- BMS: technology, supply voltage
- Type of terminals
- Type of terminal cover
- Serial and parallel assembly of cells and modules
- Type of cabinet/battery mounting
- Recycling capability

Electrical characteristics 25°C:
- BMS electrical protections
- Nominal voltage, minimum and maximum cell voltage
- Nominal voltage, minimum and maximum module voltage
- Nominal voltage, minimum and maximum system voltage
- Series assembly
- Nominal capacity of a cycle at 100% DoD and a rate of C1, C0.5
- Monthly self-discharge rate
- Cycling efficiency
- Cycling performance under C10, C1 rates (with a certain temperature and associated ageing rate)
- Permanent power consumption of the BMS
- Earthing of one polarity and associated electrical protections

General characteristics:
- Operating temperature (min/max)
- Storage temperature
- Dimensions (L x W x H)
- Total weight

Labelling:
- Manufacturer's brand
- Battery type
- Nominal voltage
- Nominal capacities at 25 degrees Celsius.
- Marking of the + and - terminals.
- Safety instructions
- Indications of conformity to standards
- Original Equipment Manufacturer (OEM) of battery cell

Warranties
Typical warranties range from 1 to 5 years, although extensions up to 10 years are sometimes offered by the manufacturers.

The lifetime can vary from 5 to 20 years under normal operating conditions. The main parameters that affect the lifetime of a Li-ion battery are:

- The internal temperature of the cells
- Number of cycles and depth of discharge per cycle (DOD)
- The quality of the charge regulation and deep discharge protection

It should be remembered that there is no simple and reliable device for testing the performance values of a battery (whatever its technology), and that the manufacturer's experience and the trust placed in them are the key elements for the correct choice of a product.

Recommendations
It is strongly recommended that the battery manufacturer, or at least the system integrator, is strongly involved in the overall design of the protective devices, installation, commissioning and configuration of the system. Unfortunately, it is quite common for this type of system to be installed in isolated areas and, after the first fault of a cell, the BMS stops the system without the possibility of restarting it by local operators.

It should be remembered that these systems are complex, and potentially dangerous. They are usually assembled and configured in their manufacturing countries, so it is difficult to transfer relevant skills to the local people that use them. Moreover, often larger systems are associated with a fleet of energy-intensive air-conditioning units that also need to be maintained.

The communication protocols between the BMS and the different chargers /hybrid inverters (multifunctional inverter, MPPT PV charge controller) are specific to each battery manufacturer, making the battery difficult to exchange in case of failure.

Li-ion battery cells should comply with the following standards:

IEC 61427-1 (As under Lead -Acid batteries)

IEC 61427-2 (As under Lead -Acid batteries)

IEC 62619 (As under battery performance)

IEC 62133 (As under Lead-Acid Batteries)

IEC 62133 (transport of Li-ion batteries)

IEC 62485-1:2015 specifies the basic requirements for secondary batteries and battery installations. The requirements regarding safety, reliability, life expectancy, mechanical strength, cycle stability, internal resistance, and battery temperature, are determined by various applications, and this, in turn, determines the selection of the battery design and technology. In general, the requirements and definitions are specified for lead-acid and nickel-cadmium batteries. For other battery systems with aqueous electrolyte, the requirements may be applied accordingly. The standard covers safety aspects taking into account hazards associated with:

- electricity (installation, charging, discharging, etc.);
- electrolyte;
- inflammable gas mixtures;
- storage and transportation.

IEC 62485-2:2015 This part of the IEC 62485 applies to stationary secondary batteries and battery installations with a maximum voltage of DC 1 500 V (nominal) and describes the principal measures for protections against hazards generated from:

- electricity,
- gas emission,
- electrolyte.

This International Standard provides requirements on safety aspects associated with the erection, use, inspection, maintenance and disposal. It covers lead-acid and NiCd / NiMH batteries. Examples for the main applications are:

- telecommunications,
- power station operation,
- central emergency lighting and alarm systems,
- uninterruptible power supplies,
- stationary engine starting,
- photovoltaic systems.

IEC 61960:2011 specifies performance tests, designations, markings, dimensions and other requirements for secondary lithium single cells and batteries for portable applications. The objective of this standard is to provide the purchasers and users of secondary lithium cells and batteries with a set of criteria with which they can judge the performance of secondary lithium cells and batteries offered by various manufacturers. This second edition cancels and replaces the first edition published in 2003. It is a technical revision. This edition includes the following significant technical changes with respect to the previous edition:

- 7.6 Endurance in cycles:
  Addition of an accelerated test procedure

Safety tests according to **IEC 60086-1:2021** are intended to standardize primary batteries with respect to dimensions, nomenclature, terminal configurations, markings, test methods, typical performance, safety and environmental aspects. This document on one side specifies requirements for primary cells and batteries. On the other side, this document also specifies procedures of how requirements for these batteries are to be standardized. As a classification tool for primary batteries, this document specifies system letters, electrodes, electrolytes, and nominal as well as maximum open circuit voltage of electrochemical systems.

Generally speaking, these storage solutions may be of interest in the following contexts:

- Climatic zone with moderate temperature (seaside, high altitude area).
- High-power hybrid power plant with a high share of solar and thermal energy, and a moderate use of storage (high charge and discharge current -considerable cycling on a daily basis).
- Very isolated area with availability of a trained and skilled maintenance team that can be quickly mobilized or remote 1st line support.
- Ideally, have a technical and commercial representation of the manufacturer (OEM) in the country of installation.

Minimum requirements
The project engineer must define the project requirements based on the considerations presented in the previous sections and the specific context of the project. The normative references listed and the minimum requirements presented in the following table should be respected in all projects.

Battery rack or module power density	≥ 60 Wh/kg
Number of cycles @ 80% DoD and @25oC	≥ 2000
Operating temperature range	At least from 10° C to 45° C

Table 8: Minimum requirements for Li-Ion batteries.

CONTROL AND DATA ACQUISITION SYSTEM (MONITORING)

Cabling and protective devices

PV connectors
To simplify the installation, plug-in connectors are used at the PV modules, PV string and sub-array combiner boxes, and at the input of the PV charge controllers.

These connectors also provide a good protection against the risk of electric shock for the installer.

The connectors must be:

- Specified for direct current
- Sized for higher voltage and current values compared to the cables
- Provide protection against direct contact (≥ IP2X or IPXXB)
- Class II
- Resistant to outdoor conditions (UV, humidity, temperature) (≥ IP55)
- compliant to IEC 62852

A "Do not disconnect under load" label must be present on each connector or, if not possible, a label must be attached near the connectors.

However, in order to prevent disconnection under load and its associated arcing, connectors accessible to unskilled or unqualified people must only be operated with the aid of a specific construction or installation tool (e.g. lockable DC connectors) and only after the corresponding DC switch has been opened.

NOTE: :
It must be specified whether the inter connect cable connectors require a specific tool (e.g. crimping pliers).

It is imperative to use male and female connectors from the same manufacturer, especially when connecting the last modules on a PV string to the corresponding string cable, or to the pre-installed connectors in some DC boxes or PV charge controllers.

PV cables/wiring (string and sub-array)
Given the specific nature of PV installations, the characteristics of PV cables must be as follows:

- Cables with XLPE insulation (Cross-linked Polyethylene)

- Cables that are at least flame-retardant and comply with the tests of IEC 60332-3-10:2018: - Tests on Electric and Optical Fibre Cables Under Fire Conditions - Part 3-10: Test for Vertical Flame Spread of Vertically-Mounted Bunched Wires or Cables - Apparatus, and consider a core temperature of at least 90°C in continuous operation.

- Cables selected to minimize the risk of earth faults or short circuits. This is ensured by using unipolar cables with an insulation equivalent to Class II (double insulation).

- UV stable, meeting condition AN3 (if not protected by screen interposition)

- Nominal voltage (Uo/U) compatible with the maximum voltage Uocmax

NOTE:
In view of the high temperatures to which PV string cables can be subjected, the sizing must take into account an ambient temperature of 70°C.

To withstand these harsh environmental conditions, cables have been developed specifically for PV applications.

The the IEC 62930: Electric cables for photovoltaic systems with a voltage rating of 1,5 KV DC standard specifies the characteristics of these cables.

Caution: Some H07RNF cable types have a maximum core temperature limited to 70°C and therefore cannot be used in PV strings. However, the H07 BN4-F cable type can withstand a maximum core temperature of 90°C and can therefore be used in a PV string as long as a temperature derating factor is taken into account when calculating the maximum admissible current.

Minimum cross-section of cables between PV generator and PV charge controller, and between PV generator and PV inverter
The cables between PV generator and PV charge controller are subject to UV rays and ambient temperatures that can reach, in the worst case, 50°C. Consequently, the use of XLPE (cross-linked PolyEthylene) cables is imperative (example: HO7RNF and U1000R2V).

The sizing of the minimum cross section of the cables can be carried out by following the calculation according to the method presented above, taking into account the value of the overcurrent protection device.

In practice, the values below can be used in case of protecting the cable via fuses (string, sub-array and array cables).

Fuse rating (A)	Minimum cross-section (mm^2) for XLPE cables, not buried	Minimum cross-section (mm^2) for XLPE cables, buried
	Ta = 50°C, installation method B-31/32, 2 circuits in 2 layers	installation method D-61, 2 joined ducts
10	1,5	1,5
16	1,5	1,5
20	2,5	2,5
25	4	4
32	6	6
40	10	10
50	10	16
63	16	25

Table 9. Cable cross-section for each fuse rating.

Minimum cross-section of the cables between the other components
For other cables installed inside the technical room, which may be subjected to high ambient temperatures that can reach e.g. 40°C, the use of XLPE cables is strongly recommended (e.g. HO7RNF and/or U1000R2V).

The sizing of the minimum cross-section of the cables connecting the main components of a system can be carried out by taking, for example, the following assumptions (assumptions which are fairly representative of the normal conditions for the DC cable installations in typical PV mini-grids) :

- XLPE cable with copper core, type HO7RNF or U1000R2V
- Cable protection by fuses, type gG
- Maximum ambient temperature: 40°C
- Installation method: single-core cables fixed on cable trays.

The table below offers a quick determination of the minimum cable cross-section according to the fuse rating, based on the above-mentioned assumptions. (WARNING: these assumptions must be double-checked against the actual conditions of the PV mini-grid).

Fuse rating (A)	Minimum cross-section (mm²) XLPE cables
	Ta = 40°C, installation method F-13 3, single-layer circuits
10	1,5
16	1,5
20	2,5
25	4
32	4
40	6
50	10
63	16
100	25
125	35
160	50
200	70
250	95
300	120

Table 10: Cross-section for each gG fuse rating

NOTE: The minimum cable cross-section is also determined by the voltage drop limitation. This parameter is often decisive for the sizing of DC cables on the PV generator side.

Voltage drops on the DC circuit

Voltage drop between PV generator and battery
The various connections between the components must be made by cables of sufficient cross-section so that the voltage drop, calculated with the maximum DC or AC current, does not exceed 3% of the nominal voltage so as to ensure a satisfactory operation (functional aspect) and to reduce energy losses (energy aspect).

By convention, the maximum voltage drop of the PV generator cables is calculated with the following assumptions:

- $I_{mpp\ stc}$ = current I_{mpp} (stc) in A at 1000 W/m².
- $U_{mpp\ stc}$ = PV generator voltage U_{mpp} (stc) in V at 1000 W/m².

In practice, the voltage drop between the PV modules and the battery is limited to a maximum value of 3%, calculated in STC conditions. The cross-section of the cables is dimensioned in such a way that the voltage drop is limited to :

- 2% of the nominal voltage of the PV string, between the PV string combiner box and the charge controller, considering the maximum charging current Impp (stc)
- 1% of the nominal voltage of the battery, between the charge controller and the battery, considering the maximum output current of the charge controller Imax.

Voltage drop between battery and multifunctional inverter
The voltage drop between the battery and the multifunctional inverter must be kept to a minimum so that the inverter measures a battery voltage that is as close as possible to reality, considering the maximum current. This is because the charge regulation functions (when in charger mode) and the discharge limitation functions (when in inverter mode) are generally based on the battery voltage thresholds seen at the terminals of the multifunctional inverter.

In practice, cable cross-sections are sized so that the voltage drop is limited to 1%, considering the maximum current drawn or supplied by the multifunctional inverter.

The maximum value of the current can be determined as:

$I_{max} = 1.5\ P_{max} / (U_{bat\ min} \times R_{inv})$

With :

- P_{max} = Higher value between the maximum charge power (continuous at 20°C) and the maximum discharge power (continuous at 20°C) of the multifunctional inverter.
- $U_{bat\ min}$ = minimum battery voltage (discharged state).
- R_{inv} = Average efficiency of the multifunctional inverter.

NOTE : The coefficient 1.5 takes into account the IRMS current, which is higher than the average current.

Voltage drop calculation methods

The DC voltage drop is given by the following formula:

$\Delta U = (\rho\ L/S) \times I$

or relative value: $\Delta U/U\ (\%) = (\rho\ L/S) \times I / U \times 100$

or :

$\Delta U = (R_L\ L) \times I$

or relative value: $\Delta U/U\ (\%) = (R_L\ L) \times I / U \times 100$

with :

- ΔU: voltage drop in V
- U: nominal voltage in V
- ρ : cable's resistivity, in Ω.mm²/m. Assuming a core temperature of 90°C, $\rho = 1.25 \times \rho_0$, ρ_0 being the resistivity of copper at 20°C. This gives ρ= 1.25 x 0.01851 =0.02314Ω .mm²/m for copper at 90°C.
- L: total length of the unipolar conductors (+) and (-), in m
- S: cable cross-section, in mm².
- I: current flowing in the cable, in A

- RL: Linear resistance of cables (RL = ρ/S), in mΩ/m

NOTE: Many online tools and calculators are available to correctly estimate voltage drops in AC and DC circuits.

Pour 12V continue	Section en mm²													
Ampérage max en ampére	0,75	1	1,5	2,5	4	6	10	16	25	35	70	95	120	150
0,5	21,43	28,57	42,86	71,43	114,29	171,43	285,71	457,14	714,29	1000,00	2000,00	2714,29	3428,57	4285,71
1	10,71	14,29	21,43	35,71	57,14	85,71	142,86	228,57	357,14	500,00	1000,00	1357,14	1714,29	2142,86
2	5,36	7,14	10,71	17,86	28,57	42,86	71,43	114,29	178,57	250,00	500,00	678,57	857,14	1071,43
5	2,14	2,86	4,29	7,14	11,43	17,14	28,57	45,71	71,43	100,00	200,00	271,43	342,86	428,57
10	1,07	1,43	2,14	3,57	5,71	8,57	14,29	22,86	35,71	50,00	100,00	135,71	171,43	214,29
15	NA	NA	1,43	2,38	3,81	5,71	9,52	15,24	23,81	33,33	66,67	90,48	114,29	142,86
20	NA	NA	1,07	1,79	2,86	4,29	7,14	11,43	17,86	25,00	50,00	67,86	85,71	107,14
25	NA	NA	NA	1,43	2,29	3,43	5,71	9,14	14,29	20,00	40,00	54,29	68,57	85,71
30	NA	NA	NA	1,19	1,90	2,86	4,76	7,62	11,90	16,67	33,33	45,24	57,14	71,43
35	NA	NA	NA	1,02	1,63	2,45	4,08	6,53	10,20	14,29	28,57	38,78	48,98	61,22
40	NA	NA	NA	NA	1,43	2,14	3,57	5,71	8,93	12,50	25,00	33,93	42,86	53,57
45	NA	NA	NA	NA	1,27	1,90	3,17	5,08	7,94	11,11	22,22	30,16	38,10	47,62
50	NA	NA	NA	NA	1,14	1,71	2,86	4,57	7,14	10,00	20,00	27,14	34,29	42,86
60	NA	NA	NA	NA	NA	1,43	2,38	3,81	5,95	8,33	16,67	22,62	28,57	35,71
70	NA	NA	NA	NA	NA	1,22	2,04	3,27	5,10	7,14	14,29	19,39	24,49	30,61
80	NA	NA	NA	NA	NA	1,07	1,79	2,86	4,46	6,25	12,50	16,96	21,43	26,79
100	NA	NA	NA	NA	NA	NA	1,43	2,29	3,57	5,00	10,00	13,57	17,14	21,43
120	NA	NA	NA	NA	NA	NA	1,19	1,90	2,98	4,17	8,33	11,31	14,29	17,86
150	NA	NA	NA	NA	NA	NA	NA	1,52	2,38	3,33	6,67	9,05	11,43	14,29
200	NA	NA	NA	NA	NA	NA	NA	1,14	1,79	2,50	5,00	6,79	8,57	10,71
250	NA	NA	NA	NA	NA	NA	NA	NA	1,43	2,00	4,00	5,43	6,86	8,57
300	NA	NA	NA	NA	NA	NA	NA	NA	1,19	1,67	3,33	4,52	5,71	7,14
350	NA	NA	NA	NA	NA	NA	NA	NA	1,02	1,43	2,86	3,88	4,90	6,12
400	NA	NA	NA	NA	NA	NA	NA	NA	NA	1,25	2,50	3,39	4,29	5,36

Table 11: Example table for calculating the maximum lengths of unipolar copper cable that can be used in a 12V DC system, considering a voltage drop of 5% - Attention: this is only an example, valid only for a given environment.

The following standards abstracts are relevant to wiring and cables used in PV mini grids::

IEC 60227-1:2024 applies to rigid and flexible cables with insulation, and sheath if any, based on polyvinyl chloride, of rated voltages Uo/U up to and including 450/750 V used in power installations of nominal voltage not exceeding 450/750 V AC.

NOTE For some types of flexible cables the term "cord" is used.

The particular types of cables are specified in IEC 60227-3, IEC 60227-4, IEC 60227-5, IEC 60227-6 and IEC 60227-7. The code designations of these types of cables are provided in this document. The test methods specified in this document, IEC 60227-3, IEC 60227-4, IEC 60227-5, IEC 60227-6 and IEC 60227-7 are given in IEC 63294, IEC 60332-1-2 and in the relevant parts of the IEC 60811 series.

IEC 60228:2023 specifies the nominal cross-sectional areas, in the range from 0,5 mm^2 to 3 500 mm^2, for conductors in electric power cables and cords of a wide range of types. Requirements for numbers and sizes of wires and resistance values are also included. These conductors include solid, stranded and Milliken, copper, aluminium and aluminium alloy conductors in cables for fixed installations and flexible copper conductors. This document does not apply to conductors for telecommunication purposes. The applicability of this document to a particular type of cable is as specified in the standard for the type of cable. Unless specified otherwise in a particular clause, IEC 60028 ED4 relates to the conductors in the finished cable and not to the conductor as made or supplied for inclusion into a cable. Conductors described in this document are specified in metric sizes. Informative annexes provide supplementary information covering temperature correction factors for resistance measurement (Annex B) and guidance on dimensional limits of circular conductors (Annex C). This document has the status of a horizontal publication in accordance with IEC Guide 108.

IEC 60502-1:2021 specifies the construction, dimensions and test requirements of power cables with extruded solid insulation for rated AC voltages of 1 kV (Um = 1,2 kV) and 3 kV (Um = 3,6 kV) for fixed installations such as distribution networks or industrial installations. Cables of rated AC voltage 1 kV (Um = 1,2 kV) designed and tested in accordance with this document can also be used, if declared by the manufacturer, in DC distribution systems having their nominal voltage ≤ 750 V DC (with a maximum of 900 V DC) between a live conductor and neutral/earth, or ≤ 1 500 V DC (with a maximum 1 800 V DC) between two live conductors. Applicable core identification for DC systems is considered in accordance with local installation regulations.

IEC 62852:2014 applies to connectors for use in the d.c. circuits of photovoltaic systems according to class II of IEC 61140:2001 with rated voltages up to 1 500 V d.c. and rated currents up to 125 A per contact. It applies to connectors without breaking capacity but which might be engaged and disengaged under voltage

IEC 62930:2017(E) applies to single-core cross-linked insulated power cables with cross-linked sheath. These cables are for use at the direct current (DC) side of photovoltaic systems, with a rated DC voltage up to and including 1,5 kV between conductors and between conductor and earth. This document includes halogen free low smoke cables and cables that can contain halogens.
The cables are suitable to be used with Class II equipment as defined in IEC 61140.
The cables are designed to operate at a normal continuous maximum conductor temperature of 90 °C. The permissible period of use at a maximum conductor temperature of 120 °C is limited to 20,000 h.

IEC 61084-1:2017 specifies requirements and tests for cable trunking systems (CTS) and cable ducting systems (CDS) intended for the accommodation, and where necessary for the electrically protective separation, of insulated conductors, cables and possibly other electrical equipment in electrical and/or communication systems installations. The maximum voltage of these installations is 1 000 V AC and 1 500 V DC. This document does not apply to conduit systems, cable tray systems, cable ladder systems, power track systems or equipment covered by other standards. This second edition cancels and replaces the first edition published in 1991 and Amendment 1:1993. This edition constitutes a technical revision. This edition includes the following significant technical changes with respect to the previous edition:

- classification;
- construction;
- mechanical and electrical properties.

This part of the IEC 61084 series is not intended to be used by itself.

This **part of IEC 61386** specifies requirements and tests for conduit systems, including conduits and conduit fittings, for the protection and management of insulated conductors and/or cables in electrical installations or in communication systems up to 1 000 V a.c. and/or 1 500 V d.c. This second edition cancels and replaces the first edition published in 1996, and its Amendment 1 (2000), and it constitutes a technical revision. The changes to the first edition are as follows:

- change to the length of the test specimen between fittings for the tensile test
- editorial and normative reference updates.

IEC TR 63216:2019 is to define homogeneous categories for the electromagnetic environments in order to harmonize as far as practicable all general rules and product standard requirements of electromagnetic compatibility (EMC), applicable to low-voltage switchgear, controlgear and their assemblies with built-in electronic circuits.
This document also addresses incorporated radiocommunication functions.
The typical application environments for such equipment include the electrical distribution in infrastructure, commercial and industrial buildings and the control systems of machinery, including motor-driven systems.
The primary intention of EMC requirements is to ensure the safe and reliable operation of the equipment, as well as the communication efficiency of the radiocommunication equipment within their intended environments.

DC bus cables
The cables used for the connections between the individual components within the DC bus must have the following characteristics:

- XLPE insulation
- At least type C2 (non-flame propagating), meeting the tests of IEC 60332-3-10:2018: Tests On Electric And Optical Fibre Cables Under Fire Conditions - Part 3-10: Test For Vertical Flame Spread Of Vertically-Mounted Bunched Wires Or Cables - Apparatus.
- Nominal voltage 0.6/1kV
- Maximum core temperature 90°C (250°C in short circuit)
- Good weather resistance
- Ambient operating temperature range from -25°C to + 60°C
- Compliant with IEC 60245-4 and IEC 60502

Cables type U1000R2V for rigid cables and H07 RNF for flexible cables meet these requirements.

NOTE: To limit the risk of short-circuits, unipolar cables should be used in all high-power DC circuits.

In order to ease the installation process and reduce the mechanical stress on the connection terminals, preference should be given to flexible multi-stranded cables type HO7 RNF.

AC bus cable (AC output of multifunctional inverter, PV inverter, diesel generator)
The cables used for the connections between the individual system components and the AC bus must have the following characteristics:

- XLPE insulation
- At least type C2 (non-flame propagating), meeting the tests of IEC 60332-3-10:2018: Tests On Electric And Optical Fibre Cables Under Fire Conditions - Part 3-10: Test For Vertical Flame Spread Of Vertically-Mounted Bunched Wires Or Cables - Apparatus.
- Nominal voltage 0.6/1kV
- Maximum core temperature 90°C (250°C in short circuit)
- Good weather resistance
- Ambient operating temperature range from -25°C to + 60°C
- Compliant with IEC 60245-4 and IEC 60502

Cable types U1000R2V for rigid cables and H07 RNF for flexible cables meet these requirements.

NOTE:
As the risks and consequences of a short circuit on the AC bus are lower, multi-stranded cables are recommended.

If flexible HO7RNF cables are used, tubular cable lugs must be crimped at the ends of all connections within the screw or cage terminals of the equipment and the TGBT.

Protective devices on the DC side
PV string and PV sub-array combiner box (if applicable)

If the PV generator consists of several strings and/or sub-arrays of PV modules, the combiner box allows them to be connected in parallel. The combiner box usually contains the following components: fuses, switch-disconnector, SDPs and any test points.

Each string of the PV generator must be able to be disconnected and isolated individually to allow electrical control without any risk to the operator. This disconnection, which can be carried out simply by means of plug-in connectors, does not present any risk for the operator, provided that it is not carried out under load. For this purpose, a DC switch-disconnector is usually integrated in each combiner box at the outgoing feeder in order to facilitate maintenance operations.

On the other hand, in order to guarantee a good level of safety, the following constructive provisions must be respected:

- Flame-retardant enclosure with a protection class of at least IP 44
- Ventilation holes to evacuate the heat released by the protections and to avoid any condensation.
- Designed to avoid any bad electrical contact (use of spring-cage terminal blocks is preferred)
- Designed to minimize the risk of short-circuit between different polarities (e.g. physical separation between positive and negative fuse holders (or terminal blocks) with appropriate insulation).
- Spacing around protections to facilitate heat dissipation
- Use of unipolar double-insulated cables in the combiner box
- Use of Class II or equivalent insulation (§ 412 of the NFC15-100 standard)
- Conformity to IEC 61439 series standards or a set of switchgear manufactured and installed in accordance with the rules from 558.2 to 558.5 of the NFC15-100 standard.

NOTE:
In practice, combiner boxes can be installed outdoors, close to the PV arrays. In this case, the enclosure must be made of UV-resistant material.

If the combiner boxes are installed outdoors, they must be lockable for safety reasons.

PV array combiner box

The PV array combiner box contains all the cables of a PV array associated with an MPPT of the PV charge controller or PV inverter. Several PV array combiner boxes can be grouped together in the same enclosure.

The following constructive provisions must be respected:

- Flame-retardant enclosure with a protection class of at least IP 44 and IK 07
- Ventilation holes to evacuate the heat released by the protections and to avoid any condensation.
- Designed to avoid bad electrical contact (use of spring-cage terminal blocks is preferred)
- Designed to minimize the risk of short-circuit between different polarities (e.g. physical separation between positive and negative fuse holders (or terminal blocks) with appropriate insulation).
- Spacing around protections to facilitate heat dissipation
- Use of unipolar double-insulated cables in the combiner box
- Use of Class II or equivalent insulation (§ 412 of the NFC15-100 standard)
- The handle of the switch disconnector must be accessible from the exterior front side in order to perform an emergency stop.
- Conformity to IEC 61439 series standards or a set of switchgear manufactured and installed in accordance with the rules from 558.2 to 558.5 of the NFC15-100 standards.

NOTE:
In practice, the PV array combiner boxes are installed in the direct vicinity of the PV charge controller or PV inverter, in the technical room, so that it is easily accessible in case of an emergency situation.

For string inverters the installation will be in close vicinity of the PV modules.

DC Battery box – distribution enclosure

The DC bus receives the unipolar cables from the DC power circuits of all PV charge controllers, multifunctional inverters and batteries.

One or more DC-BATT boxes can be installed, depending on the size of the installation. The DC-BATT box(es) contains all the following protection and switching devices:

- DC fuses or correctly rated circuit breakers to protect the various circuits,
- The DC switch disconnector(s)
- Outgoing feeders for the DC loads (if applicable)
- Possibly, current measurement shunts for the monitoring system.

The following construction provisions must be respected:

- Flame-retardant enclosure with a protection class of at least IP 44
- Ventilation holes to evacuate the heat released by the protections and to avoid any condensation.
- Designed to avoid bad electrical contact (for cables with a cross-section greater than 25 mm^2 , tubular cable lugs connected to busbars via bolted nuts are recommended)
- Designed to minimize the risks of short circuits between different polarities (e.g. physical separation between positive and negative busbars with an appropriate insulation).
- Spacing around protections to facilitate heat dissipation
- Use of unipolar cables within the enclosure
- In the case of LV operation (U > 120 V), the use of Class II or equivalent insulation is required.

- The handle of the switch disconnector must be accessible from the exterior front side in order to perform an emergency stop.

- Conformity to IEC 61439 series standards or a set of switchgear manufactured and installed in accordance with the rules from IEC 60364 installation standards.

NOTE:
In practice, DC-BATT boxes are installed in direct proximity to the batteries (in a different room from the batteries in the case of open lead-acid batteries), to reduce the length of unprotected connections to a minimum.

PV string fuse or circuit breaker (if applicable)
Where overcurrent protection is required, fuses or correctly rated circuit breakers must be installed to protect both the positive and negative polarity of each PV string or sub-array cable:

- The protections must be sized for a current value of 1.4 $I_{SC\ STC} < In < I_{RM}$

- The protections must be sized to operate at a voltage $U > U_{ocmax}$

- The fuses must comply with IEC 60269-6 (specified for PV applications, gPV marking, conventional operating current I2 = 1.45 In).

- Circuit breakers must comply with IEC 60947-2 (conventional operating current I2 = 1.3 In).

NOTE:
The IEC 60364-7-712 recommends a value of ISCMAX = 1.25 x $I_{SC\ STC}$ for any PV sub-array. The same guide recommends sizing the rated current In of PV string protections according to the formula: 1.1 x $I_{SCMAX} \leq In \leq I_{RM}$. Given that 1.25x1.1 ≈ 1.4, the compilation of both formulas leads to the relation 1.4 $I_{sc} < In < I_{RM}$

Switch-disconnector of the PV generator and battery
The PV generator switching device must be located on the PV array cable upstream of the PV charge controller or PV inverter, within the PV array combiner box, with a handle accessible from the exterior front side of the box.
As a precautionary measure, PV switch-disconnectors should also be installed in any combiner boxes. The battery switching device must be located on the battery cable or on all connecting cables from the battery.

Switching devices must comply with the following provisions specific to PV installations:

- Rated operating voltage $U_o \geq U_{OCMAX}$ or U_{DCMAX}

- Rated current In ≥ 1.25 I_{scSTC} or I_{MAXbat} (charge or discharge)

- Conformity to IEC 60947 series standards

- Equipment specific for direct current applications with a minimum use category DC21B, with its corresponding marking

- Control of emergency shutdown devices that are easy to recognize and very accessible (close to the equipment)

- Omni-polar and simultaneous electromechanical switching via direct control or remote control

NOTE:
The breaking capacity of a switch is not the same in DC or AC. The switch must be specified for DC operation.

A DC circuit breaker can replace the switch-disconnector, providing the functions of switching, isolation and cable protection if the circuit breaker is properly sized and is not polarized.

DC fuses or circuit breakers (DC bus)

In order to protect the cables in the event of a short circuit in any equipment supplied by the DC bus, an overcurrent protection device must be installed.

Fuses or circuit breakers must be installed to protect both positive and negative polarity if no polarity is connected to earth.

- The protections must be sized for a current value of 1.1 Imax.
- The protections must be sized to operate at a voltage Uo > U_{dcmax}.
- The fuses must comply with IEC 60269-6 with PV marking, with conventional operating current I2 = 1.45 In.
- The circuit breakers must comply with IEC 60947-2 (with conventional operating current I2 = 1.3 In).

NOTE:

The gG fuses size 10 x 38 are available in ratings from 2 to 32 A.

The gG fuses size 22 x 58 are available in ratings from 32 to 100 A.

Above 100A, knife-blade fuses are used.

For high temperatures (> 30°C), the nominal rating of the protection must be de-rated.

aM fuses are not suitable for direct current.

gG fuses designed for AC operation can be used for DC operation with possible derating in voltage and size (contact the manufacturer).

Similarly, AC circuit breakers may be suitable for protecting a DC circuit because the thermal trip threshold is identical, but the magnetic thresholds are offset by a factor of 1.4 from the AC curves.

In the case of high DC voltages, and in order to respect the breaking capacity, it is sometimes necessary to connect two poles of the circuit breaker in series (see manufacturer's document).

Main AC board (MACB). / AC distribution panel

The AC bus receives the multi-strand cables of the AC power circuits from all the PV inverters, multifunctional inverters and diesel generator. The AC load could also be accommodated in the same enclosure.

One or more MACBs can be installed, depending on the size of the installation.The MACB(s) contain all the following protection and switching devices:

- AC fuses or circuit breakers to protect the various circuits,
- The transfer switch(es)
- The switch disconnector(s) of the various grid feeders
- Outgoing feeders for the AC loads (if applicable)
- One or more modular meters on the main outputs and/or inputs
- Possibly, current measurement shunts for the monitoring system.

The following constructive provisions must be respected:

- Flame-retardant enclosure with a protection class of at least IP 44 and IK 07
- Ventilation holes to evacuate the heat released by the protections and to avoid any condensation.
- Designed to avoid bad electrical contact (cage or spring-cage terminal blocks)
- Spacing around protections to facilitate heat dissipation
- Use of unipolar cables within the box
- Use of Class II or equivalent insulation
- The handle of the switch disconnector must be accessible from the exterior front side in order to perform an emergency stop.
- Conformity to IEC 61439 series standards or a set of switchgear manufactured and installed in accordance with the rules from IEC 60364 installation standards.

Recommended Standards

IEC 60146-1-1:2009 specifies the requirements for the performance of all semiconductor power converters and semiconductor power switches using controllable and/or non-controllable electronic valve devices. It is primarily intended to specify the basic requirements for converters in general and the requirements applicable to line commutated converters for conversion of a.c. power to d.c. power or vice versa. Parts of this standard are also applicable to other types of electronic power converter provided that they do not have their own product standards. This fourth edition constitutes a technical revision and introduces five main changes:

- re-edition of the whole standard according to the current directives;
- correction of definitions and addition of new terms, especially terms concerning EMC, harmonic distortion and insulation co-ordination;
- the service condition tolerances have been revised according to the IEC 61000 series;
- the insulation tests have been revised considering the insulation co-ordination;
- addition of three annexes.

This **part of IEC 61386** specifies requirements and tests for conduit systems, including conduits and conduit fittings, for the protection and management of insulated conductors and/or cables in electrical installations or in communication systems up to 1 000 V a.c. and/or 1 500 V d.c. This second edition cancels and replaces the first edition published in 1996, and its Amendment 1 (2000), and it constitutes a technical revision. The changes to the first edition are as follows:

- change to the length of the test specimen between fittings for the tensile test,
- editorial and normative reference updates.

IEC 62909-1:2017 specifies general aspects of bi-directional grid-connected power converters (GCPC), consisting of a grid-side inverter with two or more types of DC-port interfaces on the application side with system voltages not exceeding 1 000 V AC or 1 500 V DC. In special cases, a GCPC will have only one DC-port interface, which is connected to a bidirectional energy-storage device. This document includes terminology, specifications, performance, safety, system architecture, and test-case definitions. The “system architecture” defines interaction between the inverter and converters. Requirements which are common, general, and independent of special characteristics of individual generators and bi-directional storages are defined. This document does not cover uninterruptible power supply (UPS) systems, which fall under the scope of IEC 62040 (all parts). Requirements for internal and external digital communication might be necessary; the interface requirements including communication with distributed energy resources are provided in a future part of IEC 62909. All EMC requirements are defined by reference to existing IEC standards. External communication requirements are out of scope of this document.

Surge Protection Devices (SPDs)
Standards IEC TS 61643-12 help in determining the proper DC and AC SPDs and as well as fuses suitable for PV installations.

The characteristics of the DC PV SPD are determined by the following criteria :

- U_{CPV}: maximum steady-state voltage of a SPD dedicated to the protection of the DC part of the PV generator (the voltage must be chosen so that the SPD does not conduct when the PV modules are at open-circuit voltage under the worst conditions; in practice, a safety factor of 1.1 is considered $U_{cpv}>1.1\ U_{oc\_stc}$)

- U_p: level of protection, which depends on the components to be protected. To be effective, U_p must be lower than the rated impulse withstand voltage Uw of the components and circuits to be protected. A safety margin of at least 20% must be kept between U_w and U_p.

- In: nominal discharge current, which shall be ≥ 5 kA with an 8/20 µs waveform

- Iimp : Shock current characterizing Type 1 arresters, which shall be ≥ 12.5 kA.

- ISCPW: short-circuit current resistance. The SPD and its disconnector (internal or external) must have an ISCPW current greater than the Iscmax of the PV generator. A SPD with an internal disconnector must also interrupt the short-circuit current generated by the battery. If this is not the case, an external disconnector specified by the manufacturer must be installed.

The U_p voltage of the external SPDs must be coordinated with the characteristics of the devices integrated in the PV charge controllers and PV inverters to be protected. The manufacturers must then provide all necessary information for the selection of the SPDs. These SPDs must comply with the standards IEC 61643-31 and IEC 61643-11:

- the IEC 61643-31 standard applies to SPDs installed on the DC part of the PV generator

- the IEC 61643-11 standard applies to SPDs installed on the AC part of the installation

Recommended Standards

IEC 61643-11:2011 is applicable to devices for surge protection against indirect and direct effects of lightning or other transient overvoltages. These devices are packaged to be connected to 50/60 Hz a.c. power circuits, and equipment rated up to 1 000 V r.m.s. Performance characteristics, standard methods for testing and ratings are established. These devices contain at least one nonlinear component and are intended to limit surge voltages and divert surge currents. This first edition of IEC 61643-11 cancels and replaces the second edition of IEC 61643-1 published in 2005. The main changes with respect of the second edition of IEC 61643-1 are the complete restructuring and improvement of the test procedures and test sequences. NOTE: The attention of National Committees is drawn to the fact that equipment manufacturers and testing organizations may need a transitional period following publication of a new, amended or revised IEC publication in which to make products in accordance with the new requirements and to equip themselves for conducting new or revised tests. It is the recommendation of the committee that the content of this publication be adopted for national implementation not earlier than 12 months from the date of publication. In the meantime, the previous edition can still be ordered by contacting your local IEC member National Committee or the IEC Central Office.

Protection of people and equipment
Photovoltaic (PV) mini-grid installations require robust protection to ensure the safety of people and equipment. A well-designed and protected PV system not only ensures safety but also enhances system longevity and performance These may include but are not limited to:

Surge Protection:
Lightning strikes pose a significant risk to PV systems due to their large and exposed locations. When lightning hits, it can cause fires and damage sensitive components within PV equipment.

Indirect lightning strikes are particularly destructive. They can harm expensive PV components, affecting system reliability.

To mitigate this risk, consider the following measures:

- Grounding/Bonding: All conductive surfaces should be directly grounded.

- Surge Protection Devices (SPDs): Install SPDs at critical points, such as MPPTs, string inverters, and array boxes. These devices divert excess energy to ground, preventing high voltage damage.

- Type 2 SPDs: These protect against overvoltage and electromagnetic effects caused by lightning.

Equipment Protection:
- PV components susceptible to damage include:

  - PV Panels: Insulation and dielectric failures can occur due to induced transient currents and voltages during lightning strikes.
  - Inverters: These are expensive and critical for industrial applications. Downtime due to inverter failure can be costly.
  - Control and Communications Equipment: Protect these devices to maintain system functionality.
- Regular maintenance and monitoring are essential to detect any issues promptly.

Safety Measures for Personnel:
- Personnel Safety: Indirect lightning strikes can be fatal if someone is within approximately 18 meters of the strike point.

- Industrial Sites: PV systems on industrial sites also jeopardize business operations and equipment.

Risk Mitigation:
Implement safety protocols, train personnel, and ensure they understand the risks associated with lightning strikes

NOTE: where applicable, recommendations in Annexes A and B of IEEE 2023.10.2021 should apply.

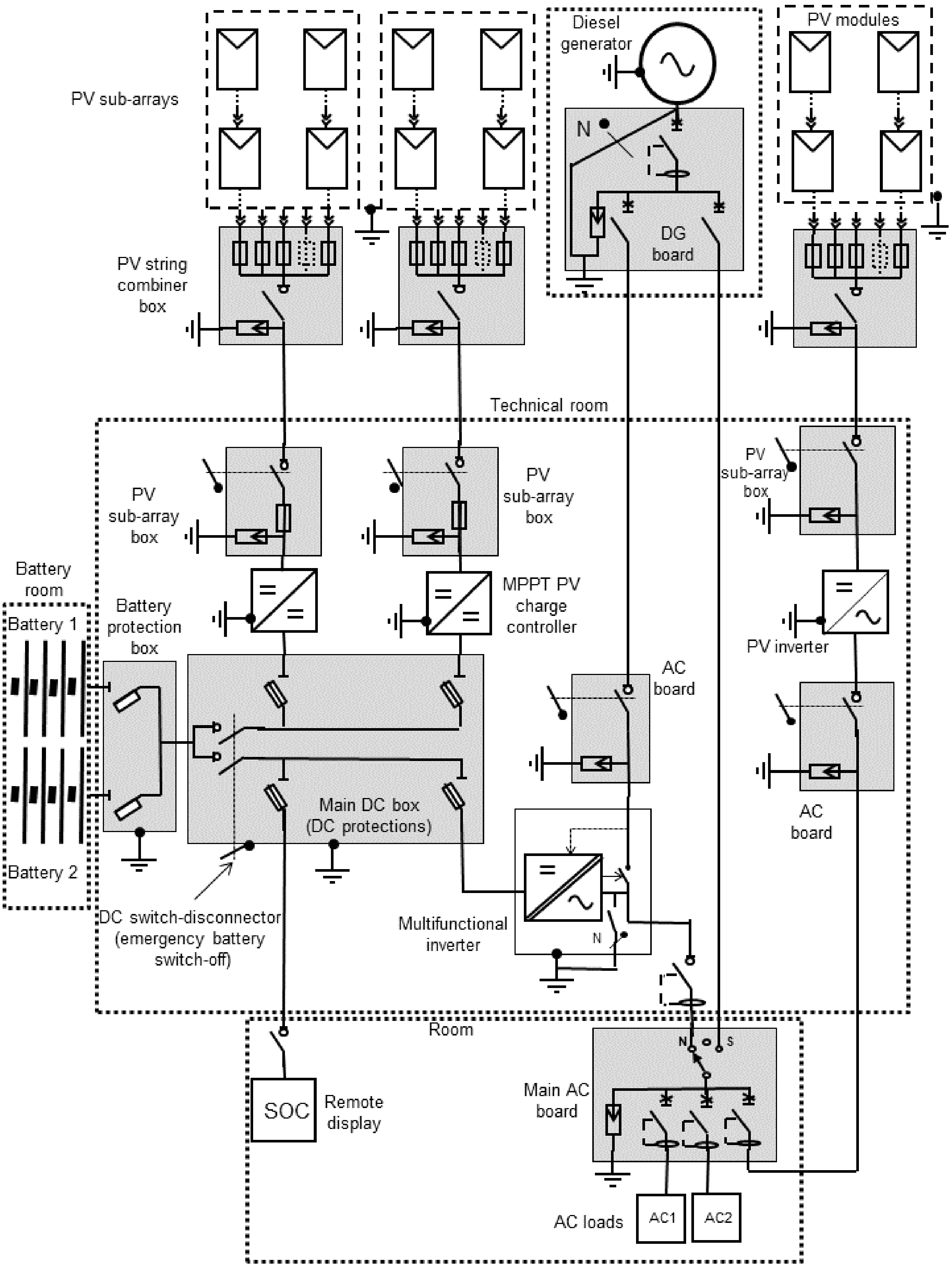


Figure 10. Single line diagram of a system with both DC-coupled and AC-coupled PV generators -

5 INSTALLATION PROCESS

The installation of a PV mini grid involves several key steps to ensure the safe and efficient deployment of the system. Proper installation practices are essential for maximizing energy generation, minimizing downtime, and ensuring the longevity of the system components.

Mounting Solar Panels
Site Preparation: Clear the installation site of debris, vegetation, and any obstructions that may shade the solar panels. Ensure the mounting surface is clean, flat, and structurally sound.

Mounting Structure Installation: Install mounting structures such as ground mounts, roof mounts, or pole mounts according to manufacturer specifications and engineering guidelines. Use appropriate anchoring methods and ensure proper alignment and spacing of the mounting rails.

Panel Installation: Secure the solar panels to the mounting structure using bolts, clamps, or brackets. Ensure panels are positioned at the optimal tilt angle and orientation to maximize solar exposure.

Connecting Components
Inverter Installation: Install the inverter in a suitable location, ensuring proper ventilation and access for maintenance. Follow manufacturer guidelines for mounting and electrical connections.

Battery Bank Installation: Position the battery bank in a well-ventilated area with adequate space for airflow and maintenance access. Connect batteries in series or parallel according to system voltage requirements.

Charge Controller Installation: Mount the charge controller in close proximity to the battery bank and solar panels. Ensure proper ventilation and secure electrical connections to the battery bank and solar array.

Wiring Setup
DC Wiring: Use appropriately sized and insulated cables for DC wiring between solar panels, charge controller, and battery bank. Minimize voltage drop and power losses by keeping wire lengths short and using proper cable routing techniques.

AC Wiring: Install AC wiring between the inverter, load center, and grid connection point (if applicable). Follow local electrical codes and regulations for safe installation practices, including proper grounding and insulation.

Protection Devices: Install circuit breakers, fuses, and surge protection devices as required to protect the PV mini-grid system from electrical faults and overloads.

The following IEC standards are relevant to the installation of PV mini grids:

IEC 62446: Grid-connected photovoltaic systems - Minimum requirements for system documentation, commissioning tests, and inspection: This standard specifies minimum requirements for documentation, commissioning tests, and inspection of grid-connected PV systems, ensuring their safe and reliable operation.

IEC 61730: Photovoltaic (PV) module safety qualification - Part 2: Requirements for construction: Part of the standard cover's safety requirements for the construction of PV modules, including mechanical integrity, electrical insulation, and protection against environmental factors.

IEC 60364: Electrical installations of buildings: This standard provides requirements and guidelines for the design, installation, and maintenance of electrical installations in buildings, including wiring, protection devices, and safety measures.

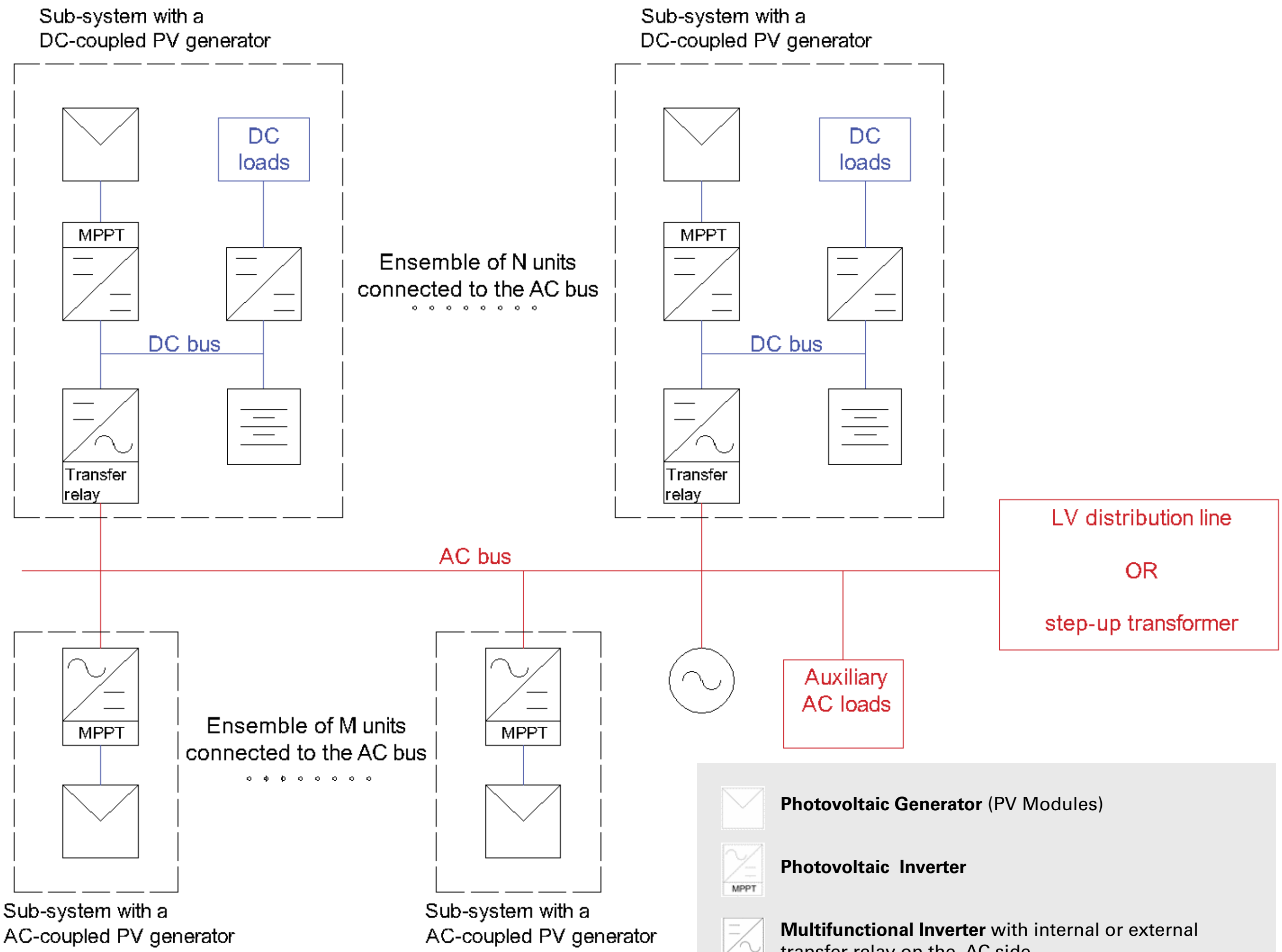
IEEE 2030.10.2021: IEEE Standard for DC Microgrids for Rural and Remote Electricity Access Applications: deals with the design and operation of a dc microgrid for rural or remote applications based on extra low voltage dc (ELVDC) to reduce cost and simplify stability are discussed in this standard. Such microgrids are typically operated without connecting to a nation's electric power system

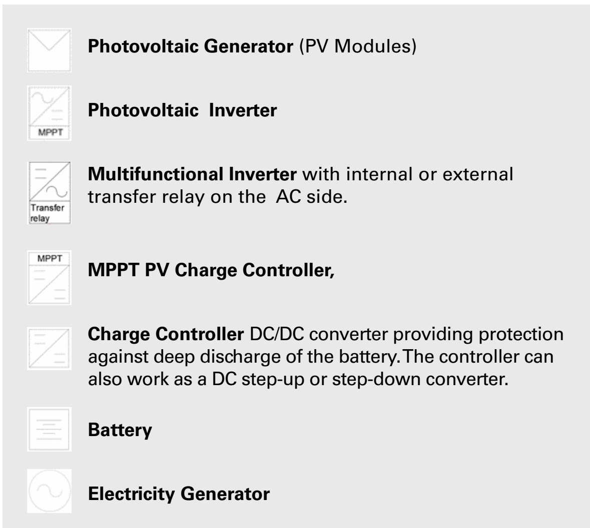
5.1 Description of the installations

5.1.1 Electrical architecture

As there are multiple mini-grid configuration options this guide references a typical generic power plant which is designed to operate in a dual configuration on both DC and AC bus, as shown in Figure 11. This generic configuration is suitable for both single-phase and three-phase systems.

NOTE: The figure shows one DC bus per DC-coupled PV generator. However, there could also be a single DC bus to be shared between all DC-coupled PV generators.





NOTE: Among the electrical architectures, the AC bus configuration without a back-up electricity generator is not accepted unless simple procedures, not requiring the intervention of qualified personnel, are available to restart the system in case of

Figure 11: Example Of A Schematic Diagram Of A Mixed Hybrid System With Both Dc-Coupled And Ac-Coupled PV Generators.

5.2 Protection of Installations

5.2.1 Protection against Atmospheric Over voltages

Introduction

Photovoltaic systems are subject, like any electrical system, to the risks induced by lightning. Components in these systems are regularly destroyed. Experience shows that the protections installed against lightning, when they exist, have often been set up without any serious study of their efficiency.

The general objective of this chapter is to provide assistance to designers and installers who have to implement lightning protection devices in stand-alone and hybrid photovoltaic power plants.

However, the practical recommendations proposed in this chapter cannot guarantee a foolproof protection against destructive effects. The objective is to achieve a significant reduction of the damage caused.

A specific study should be carried out on sites which are particularly exposed to lightning, especially in the case of using a lighting protection system.

The proposed recommendations concern protection at the level of the electrical connections of each system and assume that each component has its own internal protection characterized by a certain protection level.

5.2.2 Protection measures against the indirect effects of lightning

It should be remembered that protection against the indirect effects of lightning (overvoltages appearing on cables) requires the simultaneous implementation of several measures which will depend on the keraunic level of the zone on the one hand, and on the economic and financial analysis on the other hand.

However, in most cases, it is strongly recommended to implement the following measures:

- Uniqueness of the earthing system (connection between the lightning earthing system and the electrical installation of the technical room).

- Implementation of an equipotential network, connecting of all the electrical equipment and conductive elements of the technical room to earth.

- Installation of suitable surge protection devices (SPDs) connected to the earth terminal which shall be common with the earth of the equipment to be protected.

- Cable routing set up to avoid loops that could lead to the generation of overvoltages due to the rapidly changing magnetic field.

- Shielding of telecommunications and information transmission cables, preferably fibre optic cable should be used as they are not impacted by electrical fields.

5.2.3 Uniqueness of the earthing system and equipotentiality of the masses

If the site is equipped with a lightning protection system (LPS), the earth connections of the LPS and that of the technical room must be connected together.

On the other hand, all the metal masses of the equipment constituting the power plant, including those located in different rooms or spaces, must be interconnected by an equipotential bonding and connected to a single earth connection.

Case of a roof-mounted PV generator:

The interconnection of the metal structures of the PV generator and the masses of the electrical or electronic equipment is generally carried out with an equipotentiality conductor with a minimum cross-section of 6 mm^2.

Where several PV mounting structures are present, they must all be connected to the copper equipotential bonding conductor with a minimum cross-section of 6 mm^2, according to the UTE C15-712-2 guide.

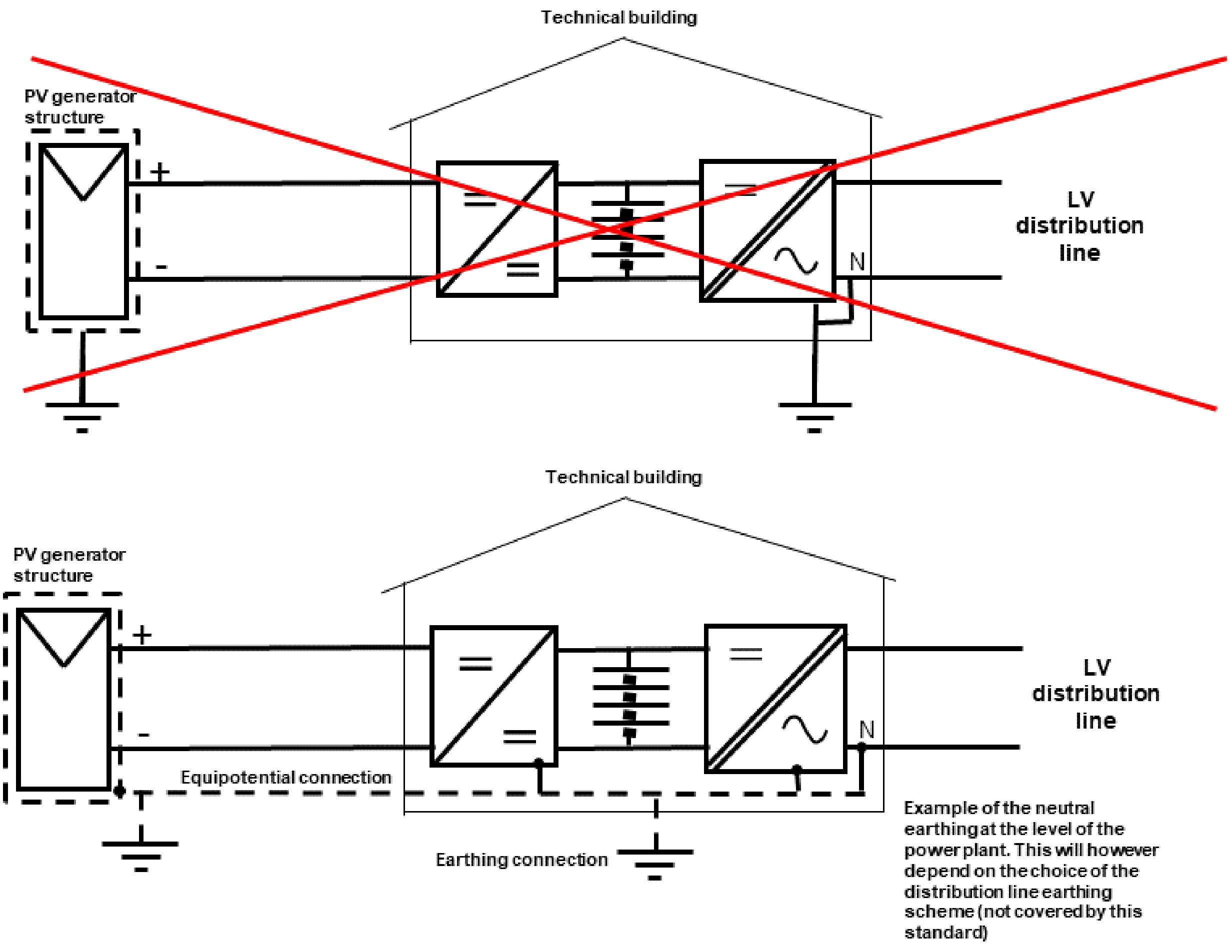


Figure 12: Examples of good and bad wiring of the equipotential bonding and earthing system

Similarly, the frame of the PV modules should be connected to the equipotential bonding conductor at one of the points provided for this purpose by the module manufacturer.

In general, all metallic pipes must be earthed near their point of entry into the building (in the case of metal ducts and shielded cables), as well as all conductive metal structures in the building.

Case of a ground-mounted PV generator:
The equipotential bonding conductor does not need to be buried if the length is less than 50 m. Above 50 m, the equipotential bonding conductor must be buried to avoid any risk of ignition which would damage the cables. A close proximity between the earth conductor and the active conductors is strongly recommended to limit the area of a potential induced loop.

When the equipotential bonding is buried, the cross section of the bare copper cable must not be less than 25 mm^2 , to minimize potential corrosion issues.

5.2.4 Metal masses of electrical equipment and accessories

The metal masses of electrical and electronic equipment (PV charge controller, PV inverters, multifunctional inverter, monitoring system, AC protection boards, etc.) must be connected directly, either to an earthing bar in the case of having SPDs, or to the nearest equipotential bonding conductor via a copper connection with a minimum cross-section of 6 mm^2 .

5.3 Basics of electrical risks

5.3.1 General considerations

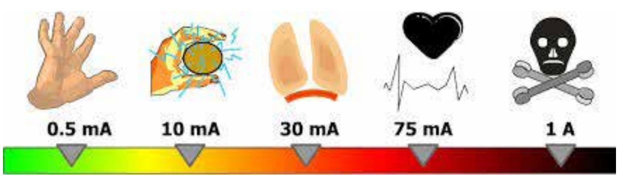
When dealing with electrical accidents, a distinction must be made between:

- Electric shocks: conducts electricity through a part of the body, or the whole body.

- Electrocution: Electric shocks with a fatal outcome.

The risks of electrical contact are twofold. On one hand, there are direct contacts where the operator touches a live part with his body. There are two possible scenarios: either the electric current flows through the body to earth (between an active conductor and earth), or the electric current flows through the body between two active conductors.
On the other hand, there are more dangerous indirect contacts where the operator touches a conductive mass (metallic or other) not connected to earth which has been accidentally energized. The current then flows through the body to earth.

In both cases, there is a risk of electrification or even electrocution. The consequences vary according to a number of parameters, for example, the presence of humidity which favors the current flow, the nature of the contacts, the health conditions of the operator, the intensity of the current which passes through the body, and the voltage difference.



The severity of danger varies depending on the person, but it is estimated that from 5 mA there could be serious consequences for the human body. These are most often injuries that mainly affect the hand, upper limbs and eyes (burns, contusions, concussions, wounds).

- From 30 mA (the trigger threshold for high-sensitivity residual current devices), there is a tetanization of the respiratory muscles which can lead to asphyxiation after a few minutes.

- Above 30 mA, "ventricular fibrillation" affects the vital organs, starting with the heart.

- Above 1 A, electrocution is unavoidable.

In order to trigger the flow of an electric current through the body, an electrical voltage must be generated between 2 parts of the body. The electrical resistance between the two live parts will determine the value of the current flowing, according to Ohm's law U=RxI.

Therefore, safety voltages are defined above which the current generated is potentially lethal for a common and healthy human being.

- Alternating current: 50 V in dry environment et 25 V in wet environment

- Direct current: 120 V in dry environment et 60 V in wet environment

Electric shocks
Electric shocks (the current flows through the body) can have different effects on humans: electrocution and internal and superficial burns. Internal burns are usually invisible, with just some marks appearing at the points of contact. They can therefore be more serious than external injuries, even though the contrary may seem.

NOTE: The higher the current, the greater the risk of sudden death. Similarly, the higher the voltage and the longer the contact time, the more dangerous the damage.

Burns
There are two types of burns caused by electricity:

- Electrothermal burns are caused by the energy dissipated by Joule effect all along the current path in the body. These burns lead to internal necrosis, particularly in the muscles.

- Arc and light radiation burns are burns caused by the projection of molten metal particles during the production of the electric arc or caused by the proximity of the body to the arc. The force of the emitted light burns the eye cells.

5.3.2 Electrical risks on the PV generator side

Electrical characteristics of a PV generator
In the case of a PV generator, the PV modules are connected in series/parallel:

- Either to a PV charge controller connected to the DC bus
- Either to a PV inverter connected to the AC bus

In both cases, the PV generator behaves like a DC current source with the following characteristics:

In optimal working conditions :

- Current I_{mpp} (Gen PV) = N_c I_{mpp} (PV module) with N_c being the number of PV strings connected in parallel
- Voltage U_{mpp} (Gen PV) = N_s U_{mpp} (PV module) with N_s being thenumber of PV modules connected in series

In short-circuit conditions :

- I_{sc} (Gen PV) = N_c I_{sc} (PV module) with N_c being the number of PV strings connected in parallel

Open circuit :

- U_{oc} (Gen PV) = N_s U_{oc} (PV module) with N_s being the number of PV modules connected in series

Therefore, all DC components (cables, switches, connectors, etc.) of the PV generator part must be selected according to the maximum current and voltage values of the certain series/parallel configuration of PV modules that comprises the PV generator.

- In voltage: $U_{oc\ max} = U_{oc}(stc) \times K_u$
- In current: $I_{scmax} = I_{sc}(stc) \times K_i$

K_u: temperature correction coefficient of the open-circuit voltage. The default value is Ku = 1.1, which corresponds to crystalline silicone modules (mono-crystalline and poly-crystalline) with a minimum cell temperature of approx. 10°C. The Ku coefficient can be calculated on a case-by-case basis depending on the minimum site temperatures.

K_i: An irradiation of 1000 W/m2 is the reference value used in the standardization of the PV modules, but the irradiation can occasionally reach 1100 to 1200 W/m2. The Ki coefficient is a safety coefficient that takes into account these irradiance peaks. In practice, Ki = 1.25 is used for crystalline silicon modules.

Summary of the main electrical risks on the PV generator side
On the PV generator side, the main electrical risks can be summarized as follows:

- Electric arcs that can start a fire. The electricity generation will be maintained while there is sun.
- Electric shocks caused by the simultaneous contact of a person with the positive and negative polarities of a PV generator with an open-circuit voltage Uoc greater than 60 V.
- Equipment damage due to the heating of a faulty PV string, which can happen if reverse currents are higher than the IRM value of the PV modules flows through the PV string.

NOTE : Shading of part of a array can also cause hot spots that could become problematic.

5.3.3 Electrical risks on the battery side

Electrical characteristics of the battery
The battery is a voltage source with the following characteristics:

Voltage:
U_n (batt) = n_s U_n (battery cell) with U_n = 2 V for a lead-acid battery and ns being the number of cells connected in series.

The maximum voltage that can be reached depends on the technology and the corresponding charging phase of the batteries:

- For open lead-acid batteries: U_{max} can reach 1.4 U_n during the equalization phase
- For sealed lead-acid batteries: U_{max} can reach 1.2 U_n during the absorption phase
- For other batteries, a U_{BATT} battery voltage value of 0.8 $U_n < U_{BATT} <$ 1.2 U_n is commonly used.

Short-circuit current :
I_{sc} (batt) = I_{sc} (cell)

The short-circuit current of a battery depends on its technology and therefore on its internal resistance, which is generally given by the manufacturers.

The Isc values of a battery are approximately:

- **Lead-acid battery:** I_{sc} = K x C_{10}, where C_{10} is capacity in ampere-hours (Ah) at a C10 rate and K=10
- **Li-Ion battery:** I_{sc} = from 100 to 200 A per cell (battery modules can consist of several hundred cells in parallel, therefore resulting in potential short-circuit currents of several tens of thousands of amps).

Specific case of the thermal runaway risk in Li-Ion batteries:
The thermal runaway of a Li-Ion cell can lead to uncontrollable chain chemical reactions, resulting in a fire, the release of toxic gases, and violent explosions. The thermal control of the Li-ion cells of a large-capacity battery is a key functionality provided by the BMS (Battery Management System) with temperature management. The risks of cell overheating can have different causes:

- High ambient temperature, or a technical room temperature which is not under control
- Abnormal heating of the cells due to overload or short-circuit on the DC bus, or excessively intensive and prolonged use.
- Internal short circuit in the cells
- Accidental damage during transport and handling phases

The use of Li-ion batteries therefore always requires firm safety measures.

Summary of the main electrical risks on the DC bus side
On the battery side and the DC bus to which it is connected, the main electrical risks can be summarized as follows:

- Electric shocks by simultaneous contact of a person with both the positive and negative polarities of a battery with a voltage higher than 60 V
- Short-circuit between the positive and negative polarities of the DC bus, which can lead to currents of several tens of thousands of amperes and thus the risk of explosion.

5.3.4 Electrical risks on the AC side

Electrical characteristics of a multifunctional inverter

The multifunctional off grid inverter operates in stand-alone mode when supplying the AC loads without a backup diesel generator. It is a device connected to a battery at its input and behaves as an AC voltage source at its output.
The electrical characteristics are as follows:

Voltage:
$U = U_n$ +/- x% where U_n is the nominal output voltage of the multifunctional inverter.

Current:

- I_n: nominal current that can be supplied continuously under certain temperature conditions
- I_{max}: maximum current that can be supplied during a specific time (typically 5 s) under certain temperature conditions.
- I_{sc}: short-circuit current that can be supplied for a very short time, typically limited to a value of around 2 to 3 times the nominal current I_n.

If the inverter is equipped with galvanic isolation, it is equivalent to a safety transformer between the DC input and the AC output of the inverter.

Electrical characteristics of a PV inverter

A PV inverter is a device that is connected upstream to a PV generator and its output is connected to the grid. It behaves like a current source with the following characteristics:

Current :

- I_n: Nominal output current of the inverter, dependent on the power of the PV generator and limited by the inverter.
- I_{sc}: short-circuit current that can be supplied by the inverter for a very short time and limited to a value of around 2 I_n .

Voltage:

The output voltage is imposed by the main grid voltage, i.e. : U_n +/- x% with U_n being the nominal grid voltage. These values and the associated ranges can be adjusted in the factory or on site depending on the product.

Electrical characteristics of a diesel generator

A diesel generator is a speed-regulated rotating machine that acts as a voltage source with the following characteristics:

- U_n +/- x% with U_n being the nominal voltage of the generator (single-phase or three-phase)
- I_n: nominal current of the generator
- S_n: apparent power of the generator
- F: nominal frequency

Short-circuit current:

The short-circuit current I_{sc} of a generator can be divided into 3 regimes:

- A sub-transitory regime that lasts 10 to 20 ms
- A transitory regime that lasts 100 to 300 ms
- A permanent regime that lasts until the protections close the circuit

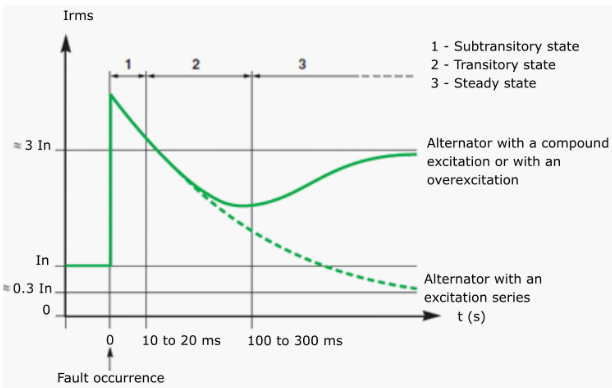


Figure 13: Transient curve of a generator set

As resistances are always negligible compared to reactance's, three impedances are defined corresponding to the three regimes and it is usual to express them by the relative voltage drop produced by the nominal current flowing through them.

For the specification of the electrical protections, only the short-circuit current corresponding to the transitory regime is taken into account, i.e., the transitory reactance, with a value on the order of 20 to 30%. The transitory reactance is defined by the ratio of the nominal current I_n to the short-circuit current I_{sc}. Very often, the type of electrical protection is recommended by the manufacturer, or directly integrated into the generator.

If it is not integrated in the generator, the circuit breaker connecting the generator to the MACB shall have a curve C and shall comply with:

1,5 x I_n diesel generator < I_n circuit breaker < 2 x I_n diesel generator

Summary of the main electrical risks on the AC bus side

The electrical risks on the AC bus side are permanent due to the continuous presence of an AC voltage of more than 50 V. The consequences of short-circuits and possible insulation faults depend on the operating mode, the earthing scheme and the characteristics of the components.

Recommended Standards

IEC 60479-1:2018(E) provides basic guidance on the effects of shock current on human beings and livestock. This basic safety publication is primarily intended for use by technical committees in the preparation of standards in accordance with the principles laid down in IEC Guide 104 and ISO/IEC Guide 51. It is not intended for use by manufacturers or certification bodies

5.4 Protection of people

5.4.1 General considerations

Risk of electric shock due to the contact with the PV cables

A single PV module does not present a risk of electric shock if the open circuit voltage is less than 60 V. However, in most PV generators, the voltage levels are higher because several PV modules are connected in series.

In some cases, the voltage at the output of the PV string (U_{oc}) can reach several hundred volts; the risk of electric shock through direct contact therefore exists.

For example, a PV string of 20 modules of 60 cells connected in series will haven open-circuit voltage of:

$$U_{oc}\ (STC) = 0.6 \times 60 \times 20 = 720\ V$$

The risk of electric arcing

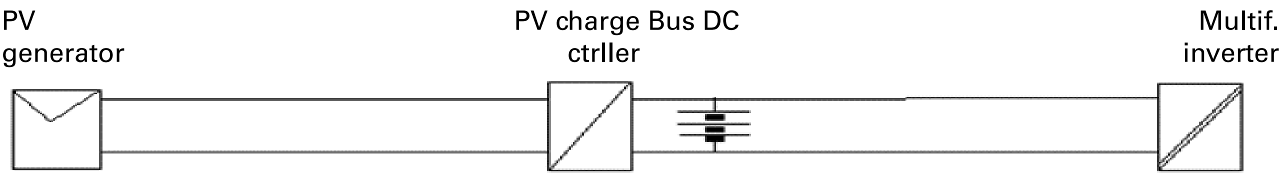
Electric arcs can cause glare, electric shock or even burns to people.

Figure 14: Example of an electric arc at the terminals of a 200 WP module under 1000 w/m² sunlight -

5.4.2 Protection against electric shocks

Protection against direct and indirect contacts on the DC side

The table below shows the personal protection measures to be taken depending on the voltage range of the DC parts (PV generator and DC bus):



Case	U_{pvmax}	Volt-age regime	Direct contact protection	Indirect contact protec-tion	Charge ctrller	Battery voltage	Voltage regime	Direct contact protection	Indirect contact protection	Multif. inverter
1	Uocstc ≤ 120V	SELV	Not needed if $U_{pv} \leq 60V$	Not needed	Without galvanic isolation	Un ≤ 120V	SELV	Not needed if Ub ≤ 60V	Not needed	With galvanic isolation
2	Uocstc ≤ 120V	PELV	Not needed if $U_{pv} \leq 30V$	Not needed	Without galvanic isolation	Un ≤ 120V with one earthed polarity	PELV	Not needed if Ub ≤ 30V	Not needed	With galvanic isolation
3	Uocstc > 120V	LV	IP2X	Class II	Without galvanic isolation	Un ≤ 120V floating	FELV	IP2X	IT earthing: Insulation con-troller, fuse in each polarity	With galvanic isolation
4	Uocstc > 120V	LV	IP2X	Class II	Without galvanic isolation	Un ≥ 120V floating	LV	IP2X	IT earthing: Insulation controller, fuse in each polarity	With galvanic isolation
5	Uocstc > 120V	LV	IP2X	Class II	Without galvanic isolation	Un ≥ 120V with one earthed polarity	LV	IP2X	TN earthing: not authorized	With galvanic isolation
6	Uocstc ≤ 120V	SELV	Not needed if $U_{pv} \leq 60V$	Not needed	Without galvanic isolation	Un ≤ 120V	SELV	Not needed if Ub ≤ 60V	Not needed	With galvanic isolation
7	Uocstc ≤ 120V	SELV	Not needed if $U_{pv} \leq 60V$	Not needed	Without galvanic isolation	Un ≤ 120V with one earthed polarity	PELV	Not needed if Ub ≤ 30V	Not needed	With galvanic isolation
3	Uocstc > 120V	LV	IP2X	Class II	Without galvanic isolation	Un ≤ 120V floating	SELV	Not needed if Ub ≤ 60V	Not needed	With galvanic isolation
9	Uocstc > 120V	LV	IP2X	Class II	Without galvanic isolation	Un > 120V floating	LV	IP2X	IT earthing: Insulation con-troller, fuse in each polarity	With galvanic isolation
10	Uocstc > 120V	LV	IP2X	Class II	Without galvanic isolation	Un > 120V with one earthed polarity	LV	IP2X	TN earthing: fuse in each polarity	With galvanic isolation

Cases 3 & 4: Protection against indirect contact is provided by the IT earthing scheme, associated with a shutdown of the charge controller and the inverter when the first fault is detected.

Case 9: Protection against indirect contact is provided by the IT regime, associated with a shutdown of the charge controller and the inverter when the first fault is detected.

Case 10: Protection against indirect contacts is provided by the TN regime, associated with a disconnection of the charge controller and the inverter when the first fault is detected by a type B RCD whose toroid is placed on the earthing connection of one of the DC polarities.

Additional protections to be considered in the case of LV

When the PV generator side or the DC bus are in the Low Voltage regime (U_{dcmax} > 120 V), the protection of people against indirect contact is ensured by a double or reinforced insulation (Class II) of the DC equipment and therefore does not require any earthing of the metal elements.

However, a possible insulation fault in the DC equipment (caused, for example, by the degradation of their insulation during installation or by aging) could have the following consequences:

- At the first fault: the voltage of the metal elements is raised above 120 V, which is potentially dangerous for people.
- The second fault: a short-circuit that can cause arcing and fire.

To limit this risk, additional protections shall be implemented:

- Interconnection of metallic masses and their earthing connection (equipotentiality principle)
- Control of the insulation between polarities and the earth
- Arrangements to prevent short circuits

Insulation monitoring

In order to monitor the insulation of the LVDC part where none of the polarities is connected to earth, an insulation monitor is usually integrated:

PV side :

- either at the PV charge controller (PV side and/or battery side)
- either at the PV inverter (PV side)
- or by a permanent Insulation Monitoring Device, for example installed in the PV array combiner box or within the components.

DC bus side:

- On the DC bus (e.g. via an Insulation Monitoring Device installed in the DC-BATT box)

At the first insulation fault, the controller detects and reports the fault so that the operator can intervene to solve the problem.
For this purpose, it is essential to earth all the metal parts of the LV PV generator, which will also help in protecting the equipment against possible lightning-induced surges.

Protection against direct and indirect contact on the AC bus

Protection against direct contact is ensured by the use of IP2X or IPXXB enclosures according to IEC 60529, which specifies the degrees of protection of electrical components according to IP rating.

First digit: solid particle protection		Second digit : Liquid ingress protection	
0	No protection	0	No protection
1	Protection against particles > 50 mm	1	Protection against vertically falling drops (dripping water)
2	Protection against particles > 12.5 mm	2	Protection against tilted ripping water with a maximum tilt of 15o
3	Protection against particles > 2.5 mm	3	Protection against spraying water (maximum tilt of 60o)
4	Protection against particles > 1 mm	4	Protection against water splashing from any direction
5	Protection against fine dust (talc)	5	Protection against water jets projected by a 6.3mm nozzle at 0.3 bar
6	Dust-tight, even microscopic	6	Protection against water jets projected by a 12.5mm nozzle at 1 bar
		7	Protection against total immersion in water up to 1 meter depth
		8	Protection against continuous immersion.

Table 12: Types of IP ratings.

Protection against indirect contact can be provided in accordance with the provisions of NFC 15-100 (French standard):

- Either by double or reinforced insulation
- Either by electrical separation
- Either by automatic power cut-off (e.g., via the diesel generator or multifunctional inverter)

In the case of coupling several AC sources together, the neutral must be earthed at a single point.

With Class I devices, a residual current device located on the connections of each source and each load, allows to completely isolate the part presenting an insulation fault.

Figure 15 shows an example of an earth connection diagram for a power plant with three AC sources: a three-phase multifunctional inverter, a three-phase diesel generator and three PV generators coupled via single-phase PV inverters .

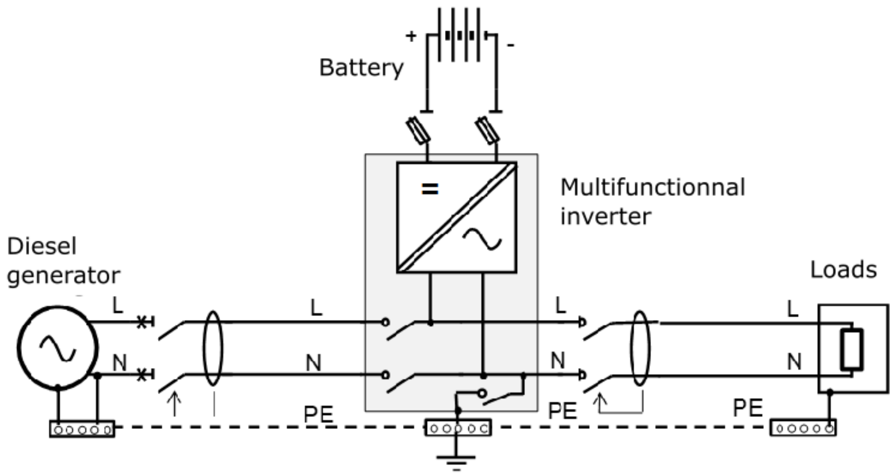


Figure 15: Example of an earth connection diagram for a hybrid system with single-phase AC bus

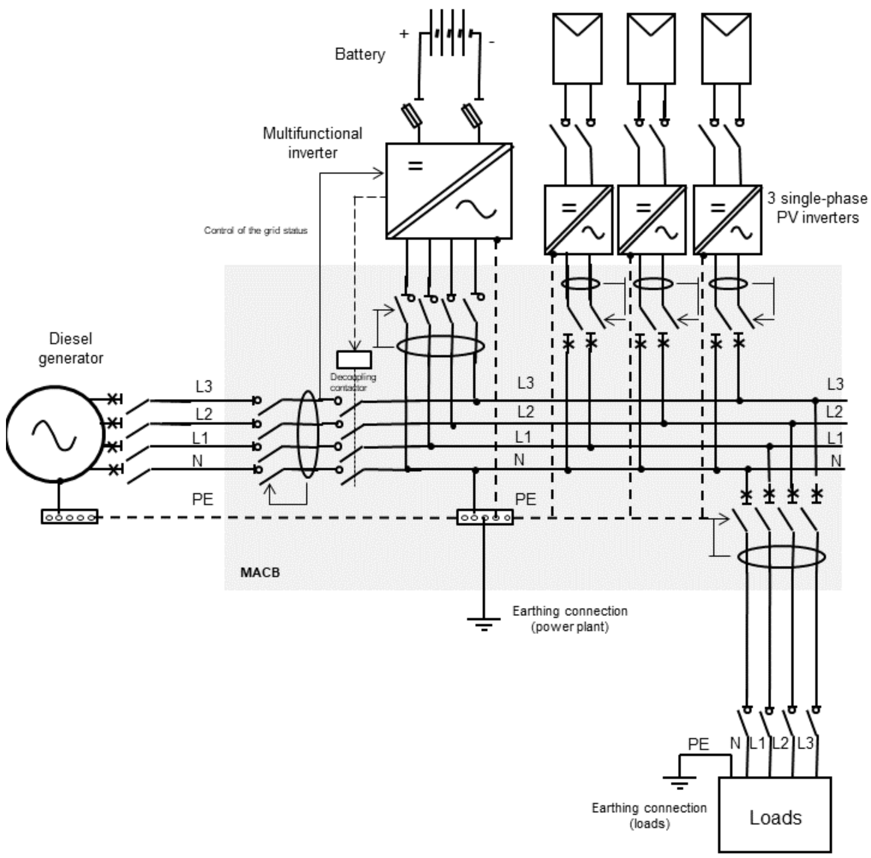


Figure 16: Example of an earth connection diagram for a hybrid system with three-phase AC bus -

5.4.3 Overcurrent protection

Introduction
It is often necessary to protect individual cables/ wiring against overcurrents in case of a potential overload or short circuit.

DC side: recommended roles and types of protection
The various examples of electrical risks show that protection is essential in order to protect the PV modules, the cables and the battery.

PV module protection: basic principles
PV modules can be damaged by reverse overcurrent if these exceed the reverse current IRM of the modules during a certain period of time. The effects of fault currents can range from permanent damage to the PV modules to the destruction of the conductors (which can lead to arcing or even fire). Dangerous fault currents can originate from a faulty PV string connected in parallel with other PV strings and, in exceptional situations, from the battery.

Consequently, overcurrent protection devices are required in most PV generators to protect the PV cables (usually on each polarity) and modules from overheating in the event of fault currents. Fuses are preferred in view of their reliability, robustness, low cost and low power dissipation.

Fault currents in PV generators are highly dependent on the incoming irradiation. They can be well below ISC (STC) and therefore may not trigger the overcurrent protection device located at each string.

In this case, these fault currents can be sources of dangerous electric arcs. Consequently, to limit the risks of short-circuit and electric arcs, the following additional provisions are often implemented:

- PV generator without any polarity connected to earth
- Unipolar DC cables with double-insulation
- Specific plug-in, Class II PV connectors
- PV string and array combiner boxes with Class II insulation
- Terminals inside combiner boxes which are physically separated

When the PV generator side is in the ELV regime ($U_{OC\ STC}$< 120 V), these additional provisions are not required.

Protection of DC bus cables: basic principles
Cables that may be overloaded by a short-circuit current from the battery must be protected against overcurrents by fuses or circuit breakers to avoid any risk of fire.

DC circuits can be protected by either fuses or circuit breakers, provided that their characteristics are suitable for direct current.

DC fuses are reliable and inexpensive, but they have a threshold value with a high tolerance and age over time, which means that they require maintenance (regular checks, replacement in case of fault).

When replacing a DC fuse it must be with the same rating fuse which is a risk if not adhered to.

DC circuit breakers are reliable, precise and stable over time, but are expensive.

Sizing of DC protections on the PV side
Reference should be made to standard IEC 60364-4-43 which refers to the general rules for protection against overcurrent.

While the design principles for DC installations remain the same as for AC installations, there are some differences regarding :

- Calculation of fault currents
- The choice of protection devices (fuses or circuit breakers) which must be specified for direct current

In order to determine the right choice for short-circuit protection, it is necessary to know the following parameters:

- Maximum I_{sc} at the origin of the cable to check against the disconnection capacity of the protection device;
- Intermediate I_{sc} to guarantee the thermal resistance of the cable. It shall be checked:
  - that the current is sufficient to activate the protections;
  - that the operating time of the protection device is less than the maximum time allowed by the cable for any value of short-circuit current.

Sizing of the PV module protection

String protection is not required if the number of strings connected in parallel N_P to an MPPT tracker of a charge controller or PV inverter is less than or equal to 2 ($N_P \leq 2$).

If $N_P > 2$, properly sized PV string fuses are able to protect the PV modules, strings and cables against reverse overcurrent.

The overcurrent protection must have a rating greater than the maximum current in normal operation and less than the reverse current I_{RM}.

The main criterion for the selection of the protection is therefore the reverse current that a PV module can withstand temporarily until the protection interrupts the fault current.

The module manufacturers give either the I_{RM} value or a maximum rated current for the fuses.

The I_{RM} reverse current is defined by IEC 61730-2 (the PV module must be able to withstand a reverse current of 1.35 I_{RM} for at least 2 hours without causing damage). It is assumed that the module can withstand a reverse current of 1.5 I_{RM} for at least 1 hour.

Therefore, the protection is effective as long as it is activated before reaching this non-destructive test value. Since the conventional melting time of string fuses is 1 h, specifically developed gPV type fuses with a melting current of $I_f \leq 1{,}45\ I_n$ can be selected with $I_n \leq I_{RM}$.

In practice, for crystalline silicon PV modules it is usual to take $I_{SC\,MAX} = 1.25\ I_{SC}$. The protection device can therefore be selected using the following formula:

$$1.4\ I_{SC}(STC) < I_n < I_{RM}$$

If I_{RM} is not known, it can be replaced by 2 ISC.

In view that the need and rating of PV fuses depends on:

- The number of parallel PV strings, N_P
- The maximum reverse current, I_{RM}

The short-circuit current at STC conditions of the PV module, $I_{SC}(STC)$

For a given type of PV module, the maximum number of parallel strings N_{cMAX} that does not require overcurrent protection is determined by the following formula:

$$N_{cMAX} \leq (1 + I_{RM}/I_{SC})$$

Sizing of PV string cable protections

The PV string cables are protected by gPV type fuses as described in the previous section. However, the cables must be correctly sized to withstand the maximum admissible current I_z.

If no protection device is needed, the maximum current Iz in the PV string cables shall be calculated as follows.

$$I_Z = 1.25\ I_{SC} \times (N_P-1) \quad \text{if } N_P \geq 2$$

$$I_Z = 1.25\ I_{SC} \quad \text{if } N_P = 1$$

If protections are needed, the determination of I_z depends on the rated current of the protection devices In defined above, and is a function of the risk of occurrence of a prolonged overload at a current level between I_n and I_2 (I_2: fuse melting current, conventional time).

The calculation of the admissible current I_Z follows the rule:

- If less than 20 PV strings are connected in parallel, the risk of occurrence is considered significant. In this case, the $I_z \geq I_2$.
- If more than 20 PV strings are connected in parallel, the risk of occurrence is not considered significant. In this case, the $I_z \geq I_n$.

NOTE: For circuit breakers complying with IEC 60947-2, the conventional operating current is $I_2 = 1.3\ I_n$. For gPV fuses, $I_2 = 1.45\ I_n$.

In practice, most cases will have less than 20 PV strings connected in parallel, thus:

If using fuses: $I_z \geq 1{,}45\ I_n$ **string**
If using circuit breakers: $I_z \geq 1.3\ I_n$ **string**

Sizing of the PV sub-array cable

In the case of a PV charge controller without galvanic isolation connected to a DC bus powered by a battery, each PV sub-array cable must be protected by an overcurrent protection device to take into account the case where the charge controller's device against reverse current is inoperative.

If the PV generator consists of a single sub-array, the maximum reverse current IREV MAX flowing in the sub-array cable is the short-circuit current IDEF BAT supplied by the battery.

$$I_{REV\ MAX} = I_{DEF\ BAT}$$

If the PV generator consists of several sub-arrays :

$$I_{REV\ MAX} = I_{DEF\ BAT} + N_a\ I_{sc\ max}\ (\text{sub-array})$$

N_a = number of PV sub-arrays in parallel.

The sizing of protection devices and cables for PV sub-arrays is based on the same principle as the sizing of protective devices for PV strings.

In practice, most cases will have less than 20 PV strings connected in parallel, thus:

If fuses are used in sub-array cables:

$$I_z > 1.45\ I_{n\ \text{sub-array}}$$

If circuit breakers are used in sub-array cables:

$$I_z > 1.3\ I_{n\ \text{sub-array}}$$

In both cases, the value of the rated current of the protective device In shall comply with:

$$I_n = 1.1\ (N_c/N_a)\ I_{sc\ max}$$

Where N_c = number of PV strings and
N_a = number of sub-arrays

Sizing of the PV array cable

In the case of a PV charge controller without galvanic isolation connected to a DC bus powered by a battery, each PV sub-array cable must be protected by an overcurrent protection device to take into account the case where the charge controller's device against reverse current is inoperative.

The maximum reverse current flowing in the PV array cable is the short-circuit current supplied by the battery, $I_{DEF\ BAT}$.

In practice, the rated current of the protection device, In, is calculated as:

$$I_n = 1.1\ I_{sc\ max\ PV\ array}$$

$$\text{And: } I_n < I_{DEF\ BAT}$$

Where $I_{sc\ max\ PV\ array} = 1.25\ I_{sc\ PV\ array}$

NOTE: In all cases, the final choice of the admissible current Iz of the PV array cables shall take into account the various correction factors defined in part 5-52 of standard NF C15-100.

Sizing of the DC bus protections on the battery side

Sizing of fuses and circuit breakers

The rules for calculating the In current for DC bus fuses are identical to the rules set out in DC Fuses or Circuit Breakers (DC Bus).

Protection of the battery cable

The battery cable must be protected against overcurrent by DC fuses or circuit breakers, in the event of a short circuit in the DC cable or DC bus.

The dimensioning of the battery cable protection device must take into account:

- the maximum current (I_{DCMAX} or I_{RMSMAX}) of the battery (in charge or discharge), taking into account any specific current peaks that may be required to start some loads.
- the potential short-circuits current of the battery ($I_{DEF\ BAT}$)

Protection of DC cables to charge controller(s) or inverter(s)
DC cables must be protected against short circuits that may occur in the equipment powered by the battery (e.g. charge controller, inverters or DC loads).

The sizing of cable protection devices must take into account:

- the maximum operating current of the devices
- the potential short-circuits current of the battery ($I_{DEF\ BAT}$).

For the cable connecting the DC bus to the inverter, the maximum power of the latter is decisive for the sizing of the protection device. The protection must not trip when the inverter is operating at its maximum power in inverter or charger mode.

In practice, the protection rated current I_n can be calculated as follows:

$$I_n > 1.1\, I_{max} \quad \text{with } I_{max} = 1.5\, P_{max} / (U_{bmin} \times R_{ound})$$

With:

U_{bmin} = minimum voltage of the battery

R_{ound} = average efficiency of the multifunctional inverter

NOTE: The coefficient 1.5 allows to use the RMS value of the inverter's input current (presence of a non-negligible ripple factor).

Implementation of SPDs
The use of SPDs allows the protection of sensitive electrical or electronic equipment which would not withstand an overvoltage exceeding the impulse withstand voltage Uw between the active conductors and earth.

In which case should SPDs be considered? Whether or not it is necessary to install SPDs is determined by a lightning risk assessment which depends on the following elements:

- The lightning strike density of the zone Ng or keraunic level Nk (an approximate relationship is Nk=10*Ng)
- Presence of overhead AC distribution lines
- Topography of the site
- Impulse withstand voltage of the various components (U_w)
- Value and importance of the components to be protected
- Consequences of possible failures
- Ability of the operator to intervene and supply with spare components.

The evaluation method used can be, for example, the one described in IEC 62305-2. Based on the existing experience with PV hybrid installations, lightning protection measures can be divided into 3 levels depending on the risk involved and the cost of implementing the protection.

Level A: very low lightning risk, Ng < 1.5
- No protection

Level B: average lightning risk, 1.5 < Ng < 2.5
- Interconnection of all conductive masses and earthing
- Protection by Type 2 SPDs on external connections
- Specific protection on other external lines (telecommunications, etc.)

Level C: significant lightning risk , Ng > 2.5
- Interconnection of all conductive masses and earthing
- External protection via a LPS (lightning rods)
- Protection by Type 1 and Type 2 SPDs on electrical connections
- Protection in steps in case of an overhead distribution network (mini-grid)
- Specific protection on other external lines (telephone, etc.)
- Shielding of sensitive cables

In practice, PV mini-grids in Africa are considered to be at risk level B or C.

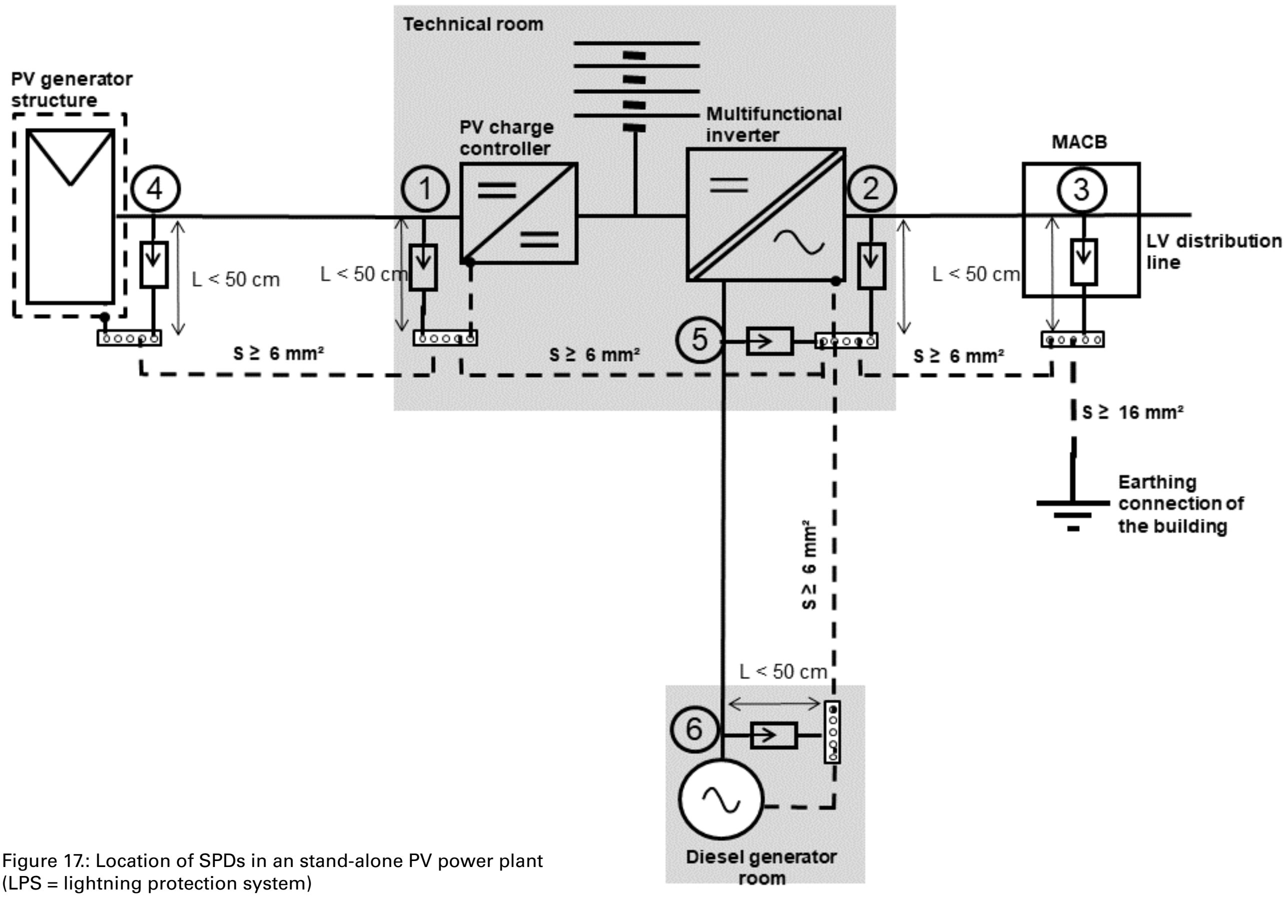


Figure 17.: Location of SPDs in an stand-alone PV power plant
(LPS = lightning protection system)

Location of SPDs
Generally speaking, the electrical and electronic equipment must be protected against overvoltages by SPDs installed on either side of the various external connections to the technical room.

Therefore, all cables entering and leaving the building (high and low current) must be protected against overvoltage with reference to the local earth.

The diagram above shows an example of the different locations of the SPDs, as well as the type and basic principles for the wiring between the different equipotential connections.

The DC SPD for L < 50 cm as illustrated in figure 17 position 4 is not necessary if:

- The distance between the PV charge controller and the PV generator is less than 10 m.

or

- The distance between the PV charge controller and the PV generator is more than 10 m, but the protection level (U_p) of the SPD installed at location 1 is less than or equal to 50% of the Uw value of the PV generator.

AC SPDs are not necessary if the electrical distribution and the diesel generator are located in the same building as the inverter.

SPDs at locations 2 and 5 are required when the AC switchboard and the diesel generator are outside the technical room.

The surge arrester at location 6 is not necessary if:

- The distance between the inverter and the diesel generator is less than 10 m.

or

- The distance between the inverter and the diesel generating is more than 10 m, but the protection level (U_p) of the SPD installed at location 5 is less than or equal to 50% of the Uw value of the diesel generator.

In the case of a mini-grid with an overhead distribution line, if the distance between the SPD at location 3 and the inverter is less than 10 m, the SPD at location 2 is not required but a SPD is required at location 3.

AC SPDs
The type of SPD depends on the earthing scheme. The IEC 61643-12 guides can be used to determine the appropriate SPDs for low-voltage electrical installations.

SPDs coordination
In practice, in order to comply with IEC 60664-1 and IEC 61000-4-5 shock immunity standards for electrical equipment, the manufacturers of PV charge controllers and multifunctional inverters generally incorporate varistors of small diameter on the DC and AC sides.

Therefore, when an SPD is installed upstream on the same line, it is necessary to ensure coordination and their respective behaviour in the event of an overvoltage.

Installation constraints requiring the two SPDs to be separated a certain cable length (or between the SPD and the equipment to be protected if the latter integrates an SPD at the input) may be necessary (according to IEC 61643-12).

Cable management
The magnetic field generated by lightning creates overvoltage in wiring loops, and these are proportional to the intensity of the lightning strike, the area and position of the loop, and the inverse of the distance to the point of impact.

To limit these overvoltages, cable management strategies shall consider the two possible types of induction loops that can occur:

Loop induced by active conductors
PV generators are generally made-up of PV strings with several PV modules. In the event of a direct lightning strike in the vicinity of a PV generator, an overvoltage is created between the positive and negative conductors of the PV generator if they are not joined.

In the most unfavorable cases, an induced voltage is transmitted directly to the DC input of electrical equipment and can cause their destruction.

Consequently, when wiring PV modules, care must be taken not to make large loops, ensuring that the positive and negative conductors are joined along their entire length.

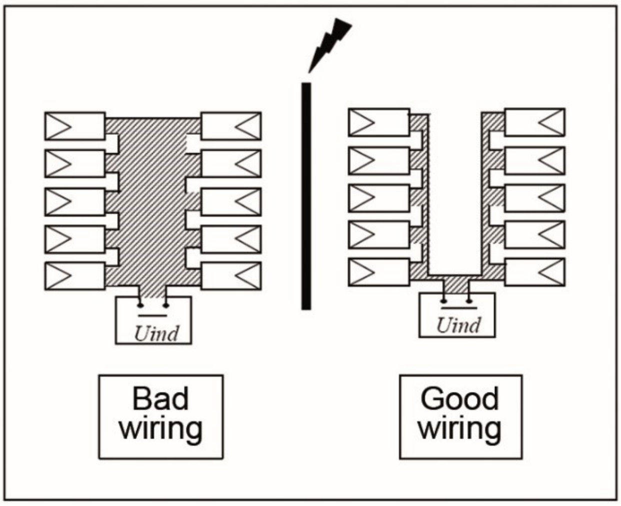


Figure 18: Example of a wiring loop between active conductors -

Loop induced by active conductors and the earth conductor
Another loop may be induced between the active conductors of the DC circuit and the equipotential bonding conductor if these are not joined when routing the cables to the electrical equipment (see below). This overvoltage can cause destructive breakdown of electrical equipment or PV modules.

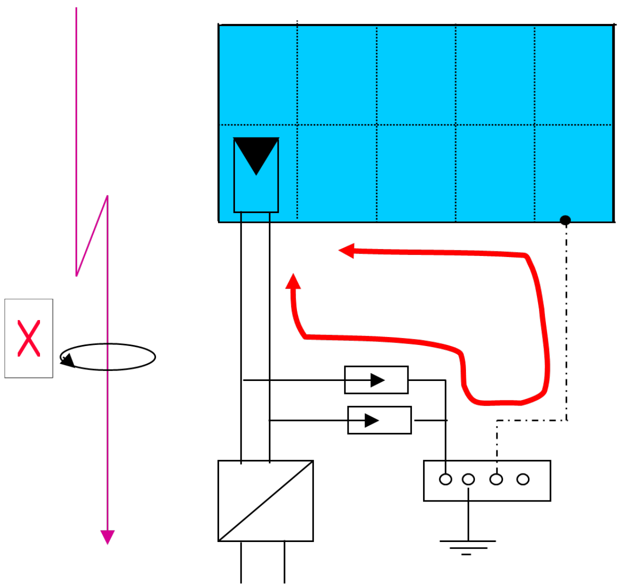


Figure 19: Example of a wiring loop between active conductors and the earth conductor

Consequently, care must be taken to ensure that the cables between the PV generator and the electrical equipment are pressed along their entire length against the earthing cable. Additional protection, such as shielding, increases the degree of protection.

Earthing and Lightning Protection

Protection measures against the direct effects of lightning
Connection of parts of a PV system to earth affects:

- The electric shock risk to people in the vicinity of the installation
- The risk of fire under fault conditions
- Transmission of lightning induced surges
- Electromagnetic interference

An earth connection for the negative pole should be established in one place to further mitigate risks, ensuring the negative pole is touch-safe during normal operation.
Recommendations are provided on how and where to establish the earth connection.
Both source and load devices attached to the microgrid should operate normally if the earth attachment of the negative pole is disconnected, except for functions related to earth fault detection.
Lightning strikes near or on the microgrid can generate short-duration, high-current impulses, making either or both poles unsafe, even with the negative pole connected to earth due to the reactive impedance of the wiring at high frequencies associated with a pulse.

Recommendations are provided on how to protect the microgrid from lightning strikes.

Two types of connection to earth are considered:

a. Earthing of exposed conductive parts (eg. the array frame)

b. System earths – where an array output cable is connected to earth

The earthing arrangements recommended in this guide are based upon those given in IEC 62305-1, IEC 62305-3, IEC 60364-1 and IEEE 2030.10.2021

Earthing of exposed conductive parts (array frame)
The majority of installations will utilise class II modules, class II d.c. cables & connectors and be connected to the mains via an inverter with an isolation transformer. This approach is recommended and permits the array frame to be left floating.

System earthing (d.c. Conductor earthing)
The bonding to earth of any of the current carrying d.c. conductors is not recommended. However as in the note below, earthing of one of the live conductors of the d.c. side is permitted, if there is at least simple separation between the a.c. side and the d.c. side, including in the inverter.

NOTE: In some countries it has been the practice to bond one part of the d.c. current conductors to earth (eg earth connection at midpoint of PV string or earthed d.c. negative), or for performance reasons on certain types of modules to earth the d.c. positive. Due to the increased possible earth fault paths, and possible problems with commonly available inverter types and internal earth fault detection circuitry, such practice should only be made when unavoidable (any connections with earth on the d.c. side should be electrically connected so as to avoid corrosion).

Inverter Earthing
The inverter must be treated as standard electrical apparatus and earthed as per BS 7671 in accordance with Class 1.2.2.4 Lightning and surge protection.

Lightning can cause damage either from a direct strike or from surges due to a nearby strike. Induced surges are the more likely cause of lightning damage in the majority of installations, especially in rural areas where electricity supplies are usually long overhead lines. Surges may be induced on both the PV array conductors or the a.c. cables leading to the building.

Lightning Protection Systems
Where there is a perceived increase in risk of direct strike as a consequence of the installation of the PV system, specialists in lightning protection should be consulted with a view to installing a separate lightning protection system in accordance with BS 6651.

NOTE: It is generally accepted that the installation of a typical roof-mounted PV system presents a very small increased risk of a direct lightning strike. However, this may not necessarily be the case where the PV system is particularly large, where the PV system is installed on the top of a tall building, where the PV system becomes the tallest structure in the vicinity or where the PV system is installed in an open area such as a field

If the building or dwelling is fitted with a lightning protection system (LPS), a lightning protection installer should be consulted as to whether, in this particular case, the array frame should be connected to the LPS, and what size conductor should be used.

NOTE: In some cases, it may be possible to forgo bonding to the LPS if the array frame is sufficiently far away from it. A system for determining whether it is necessary can be found in IEC 62305-1. Alternatively, consult the installers of the LPS.

Where an LPS is fitted, PV system components should be mounted away from lightning rods and down leads (see IEC 62305-1). For example, an inverter should not be mounted on an inside wall that has a down lead running just the other side of the brickwork on the outside of the building.

Surge Protection measures

All d.c. cables should be installed to provide as short runs as possible, and positive and negative cables of the same string or main d.c. supply should be bundled together, avoiding the creation of loops in the system. This requirement for short runs and bundling includes any associated earth/bonding conductors.

Long cables (e.g. PV main d.c. cables over about 50 m) should be installed in earthed metal conduit or trunking, or be screened cables such as mineral insulated or armoured.

NOTE: These measures will act to both shield the cables from inductive surges and, by increasing inductance, attenuate surge transmission. Be aware of the need to allow any water or condensation that may accumulate in the conduit or trunking to escape through properly designed and installed vents.

Most grid connect inverters have some form of in-built surge suppression, however discrete devices may also be specified.

NOTE:

a) To protect the a.c. system, surge suppression devices may be fitted at the main incoming point of a.c. supply (at the consumer's cut-out).

b) To protect the d.c. system, surge suppression devices can be fitted at the inverter end of the d.c. cabling and at the array.

c) To protect specific equipment, surge suppression devices may be fitted as close as is practical to the device.

Recommended standards:

IEC 61643-12:2020 Low-voltage surge protective devices - Part 12: Surge protective devices connected to low-voltage power systems - Selection and application principles – this describes the principles for the selection, operation, location and coordination of SPDs to be connected to 50/60 Hz AC power circuits, and equipment rated up to 1 000 V RMS. These devices contain at least one non-linear component and are intended to limit surge voltages and divert surge currents.

NOTE 1 Additional requirements for special applications are also applicable, if required.

NOTE 2 IEC 60364 and IEC 62305-4 are also applicable.

NOTE 3 This standard deals only with SPDs and not with surge protection components (SPC) integrated inside

6 TESTING AND COMMISSIONING

Testing and commissioning are critical phases in the deployment of a PV mini-grid system, ensuring that all components function correctly, safety measures are in place, and performance meets design specifications. This section outlines the procedures and standards for testing and commissioning PV mini-grid systems.

6.1 System Check

- **Visual Inspection:** Conduct a visual inspection of all components, including solar panels, inverters, batteries, and wiring, to ensure proper installation and connection. Check for any physical damage, loose connections, or signs of corrosion.

- Electrical Testing: Perform electrical tests, such as continuity checks, insulation resistance tests, and polarity checks, to verify the integrity and safety of the wiring and electrical connections. Use calibrated testing equipment and follow standard testing procedures.

6.2 Battery Performance Test

- **Capacity Test:** Conduct a capacity test on the battery bank to verify its energy storage capacity and performance. Discharge the batteries at a controlled rate and measure the voltage and current over time to assess capacity and voltage stability.

- **Cycle Test:** Perform a cycle test to evaluate the battery's cycle life and efficiency. Charge and discharge the batteries multiple times under realistic operating conditions to simulate real-world usage and assess long-term performance.

6.3 Inverter Test

- **Functionality Test**: Test the functionality of the inverters by connecting them to the solar array and load center. Verify proper operation of features such as maximum power point tracking (MPPT), grid synchronization, and voltage regulation.

- **Grid Connection Test:** If applicable, conduct grid connection tests to ensure seamless integration with the utility grid. Verify compliance with grid connection standards and regulations, including frequency synchronization, voltage regulation, and anti-islanding protection.

Recommended standards:

System Check

IEC 60364: Electrical installations of buildings: This standard provides requirements and guidelines for the design, installation, and maintenance of electrical installations in buildings, including wiring, protection devices, and safety measures. It covers aspects relevant to ensuring the safety and integrity of electrical systems during the system check phase.

IEC 60529: Degrees of protection provided by enclosures (IP Code): This standard defines the degrees of protection provided by enclosures against the intrusion of solid objects (including body parts like hands and fingers) and liquids. It is relevant for assessing the environmental protection of components during visual inspection.

IEC 61140:2016 applies to the protection of persons and livestock against electric shock. The intent is to give fundamental principles and requirements which are common to electrical installations, systems and equipment or necessary for their coordination, without limitations with regard to the magnitude of the voltage or current, or the type of current, and for frequencies up to 1 000 Hz. It has the status of a basic safety publication in accordance with IEC Guide 104. This fourth edition cancels and replaces the third edition published in 2001 and Amendment 1:2004. This edition constitutes a technical revision

Battery Performance Test

IEC 62619: Secondary cells and batteries containing alkaline or other non-acid electrolytes - Safety requirements for secondary lithium cells and batteries, for use in industrial applications: This standard specifies safety requirements for secondary lithium cells and batteries used in industrial applications, including performance tests such as capacity, cycle life, and safety characteristics.

IEC 61427: Secondary cells and batteries for renewable energy storage - General requirements and methods of test: This standard provides general requirements and test methods for secondary cells and batteries used in renewable energy storage applications, including performance tests relevant to battery performance testing in PV mini-grid systems.

Inverter Test

IEC 61683: Photovoltaic (PV) systems - Power conditioners - Procedure for measuring efficiency: This standard specifies the procedure for measuring the efficiency of power conditioners, including inverters used in PV systems. It provides guidelines for conducting efficiency tests under various operating conditions.

IEC 61850-7-4: Communication networks and systems for power utility automation - Part 7-4: Basic communication structure - Compatible logical node classes and data classes: This standard defines communication protocols and data formats for power utility automation systems, including inverters. It is relevant for testing the communication interfaces and interoperability of inverters in PV mini-grid systems.

Other Standards

IEC 62446: Grid-connected photovoltaic systems - Minimum requirements for system documentation, commissioning tests, and inspection: This standard specifies minimum requirements for documentation, commissioning tests, and inspection of grid-connected PV systems, ensuring their safe and reliable operation.

IEC 61724-1: Photovoltaic System Performance Monitoring - Guidelines for Measurement, Data Exchange, and Analysis - Part 1: Performance Monitoring Principles: This standard provides guidelines for performance monitoring of photovoltaic systems, including aspects related to system commissioning and testing.

IEC 60502-1:2021: Power cables with extruded insulation and their accessories for rated voltages from 1 kV (Um = 1,2 kV) up to 30 kV (Um = 36 kV) - Part 1: Cables for rated voltages of 1 kV (Um = 1,2 kV) and 3 kV (Um = 3,6 kV)

IEC 62446-1:2016 defines the information and documentation required to be handed over to a customer following the installation of a grid connected PV system. It also describes the commissioning tests, inspection criteria and documentation expected to verify the safe installation and correct operation of the system. It is for use by system designers and installers of grid connected solar PV systems as a template to provide effective documentation to a customer. This new edition cancels and replaces IEC 62446 published in 2009 and includes the following significant technical change with respect to IEC 62446:2009: expansion of the scope to include a wider range of system test and inspection regimes to encompass larger and more complex PV systems.

IEC 61730-2:2016 provides the testing sequence intended to verify the safety of PV modules whose construction has been assessed by IEC 61730-1. The test sequence and pass criteria are designed to detect the potential breakdown of internal and external components of PV modules that would result in fire, electric shock, and/or personal injury. The standard defines the basic safety test requirements and additional tests that are a function of the PV module end-use applications. Test categories include general inspection, electrical shock hazard, fire hazard, mechanical stress, and environmental stress. This new edition includes the following significant technical changes with respect to the previous edition:

- the test sequences have been rearranged;
- various tests have been detailed or added. IEC 61140:2016 applies to the protection of persons and livestock against electric shock. The intent is to give fundamental principles and requirements which are common to electrical installations, systems and equipment or necessary for their coordination, without limitations with regard to the magnitude of the voltage or current, or the type of current, and for frequencies up to 1 000 Hz. It has the status of a basic safety publication in accordance with IEC Guide 104.

7 OPERATIONS AND MAINTENANCE

Regular maintenance is essential for ensuring the continued performance, reliability, and safety of PV mini-grid systems. This section outlines key maintenance tasks and best practices to maximize system uptime and longevity.

7.1 Regular Checks

- **Visual Inspection:** Conduct routine visual inspections of all system components, including solar panels, inverters, batteries, and wiring. Look for signs of damage, corrosion, loose connections, or debris accumulation.

- **Electrical Testing:** Perform periodic electrical tests, such as voltage measurements, insulation resistance tests, and continuity checks, to identify any wiring faults or degradation in electrical connections. Use calibrated testing equipment and follow standard testing procedures.

- **Monitoring:** Monitor system performance regularly using data logging and monitoring equipment. Analyze energy production, battery charge, and system efficiency to identify any deviations from expected performance levels.

7.1.1 Cleaning

- **Solar Panel Cleaning:** Clean solar panels periodically to remove dust, dirt, and debris that can reduce energy output. Use a soft brush or sponge with mild detergent and water to gently clean the panels. Avoid abrasive materials that could scratch the surface.

- **Inverter and Battery Maintenance:** Inspect inverters and batteries for dust build-up or debris accumulation that can hinder heat dissipation and reduce performance. Clean the exterior surfaces with a soft cloth or brush and ensure proper ventilation around the equipment.

7.1.2 Troubleshooting

- **Fault Identification:** Develop a systematic approach to troubleshooting system faults and failures. Use diagnostic tools such as multimeters, clamp meters, and thermal imaging cameras to identify and isolate the root cause of problems.

- **Component Replacement:** Replace faulty or damaged components promptly to prevent further damage to the system. Keep spare parts on hand for critical components such as inverters, charge controllers, and batteries to minimize downtime.

7.1.3 Preventive Maintenance

- **Schedule Maintenance:** Establish a regular maintenance schedule based on manufacturer recommendations, system performance data, and environmental conditions. Schedule maintenance tasks such as inspections, cleaning, and component testing at regular intervals.

- **Record Keeping:** Maintain detailed records of all maintenance activities, including dates, tasks performed, and any issues identified. Use maintenance logs and documentation to track system performance over time and identify recurring problems.

Recommended maintenance Standards

IEC 62446-2:2020 describes basic preventive, corrective, and performance related maintenance requirements and recommendations for grid-connected PV systems. The maintenance procedures cover:

- Basic maintenance of the system components and connections for reliability, safety and fire prevention
- Measures for corrective maintenance and troubleshooting
- Worker safety

This document also addresses maintenance activities for maximizing anticipated performance such as module cleaning and upkeep of vegetation. Special considerations unique to rooftop or ground-mounted systems are summarized.

IEC 61724-1: Photovoltaic System Performance Monitoring - Guidelines for Measurement, Data Exchange, and Analysis - Part 1: Performance Monitoring Principles: This standard provides guidelines for performance monitoring of photovoltaic systems, including aspects related to maintenance and troubleshooting.

7.2 Safety Precautions

Safety is paramount when working with PV mini-grid systems. Proper safety precautions must be followed to protect personnel, property, and the environment from potential hazards. This section outlines essential safety measures and guidelines for ensuring safe operation and maintenance of PV mini-grid systems.

7.2.1 General Safety Guidelines

- **Training and Certification:** Ensure that personnel involved in the installation, operation, and maintenance of PV mini-grid systems receive adequate training and certification. Training should cover electrical safety, system operation, emergency procedures, hazard mitigation and fault reporting procedures.

- **Personal Protective Equipment (PPE):** Provide and enforce the use of appropriate PPE, including safety helmets, gloves, safety glasses, and insulated tools when working with PV mini-grid systems. Insulated footwear and fall protection equipment may also be required for working at heights.

- **Safety Signage and Barriers:** Clearly mark hazardous areas and equipment with warning signs and barriers to prevent unauthorized access and minimize the risk of accidents. Use lockout/tagout procedures when servicing or repairing equipment to prevent accidental energization.

7.2.2 Electrical Safety

- Isolation and Lockout/Tagout: Before performing any maintenance or repair work, isolate the PV mini-grid system from the power source and implement lockout/tagout procedures to prevent accidental energization. Verify that all circuits are de-energized using a voltage tester before commencing work.

- **Grounding and Bonding:** Ensure that all metallic components of the PV mini-grid system, including frames, mounting structures, and enclosures, are properly grounded and bonded to prevent electric shock hazards. Follow local electrical codes and standards for grounding requirements.

7.2.3 Equipment Protection

- **Overcurrent Protection:** Install overcurrent protection devices, such as fuses or circuit breakers, to safeguard equipment and wiring from damage caused by excessive current flow or short circuits. Size protection devices according to equipment ratings and installation requirements.

- **Surge Protection:** Implement surge protection devices (SPDs) at critical points in the PV system to protect sensitive equipment from voltage spikes and transient overvoltages. Install SPDs at the PV array, inverter input/output, and load center to mitigate the risk of equipment damage.

7.2.4 Fire Prevention and Suppression

- **Fire Detection Systems:** Install fire detection systems, such as smoke detectors and heat sensors, in areas where PV equipment is located to provide early warning of potential fire hazards. Integrate fire detection systems with building alarm systems for rapid response.

- **Fire Suppression Equipment**: Equip PV installations with fire suppression equipment, such as fire extinguishers, fire blankets, or automatic sprinkler systems, to control and extinguish fires in the event of an emergency. Ensure that fire suppression equipment is readily accessible and regularly maintained.

7.2.5 Working at Heights

- **Fall Protection:** Implement fall protection measures, such as guardrails, safety nets, or personal fall arrest systems, when working at heights above specified thresholds. Ensure that all equipment and anchor points are rated for the intended load and are regularly inspected for defects.

- **Safe Access and Egress**: Provide safe access and egress to elevated work areas, such as rooftop installations or elevated platforms. Use ladders, scaffolding, or aerial lifts equipped with appropriate fall protection features and ensure that workers are trained in their safe use.

7.2.6 Emergency Preparedness

- **Emergency Response Plan:** Develop and implement an emergency response plan that outlines procedures for responding to accidents, injuries, fires, and other emergencies. Ensure that all personnel are trained in emergency procedures and know how to access emergency resources.

- **First Aid and Fire Suppression**: Maintain fully stocked first aid kits and fire extinguishers at accessible locations throughout the worksite. Train personnel in first aid techniques and fire suppression methods to respond effectively to medical emergencies and fire incidents

Recommended related IEC Standards

IEC 60364: Electrical installations of buildings: This standard provides requirements and guidelines for the design, installation, and maintenance of electrical installations in buildings, including safety measures for PV mini-grid systems.

IEC 61439: Low-voltage switchgear and controlgear assemblies: This standard specifies requirements for the design, construction, and testing of low-voltage switchgear and control gear assemblies, ensuring their safe and reliable operation in PV mini-grid systems.

List of Useful Standards

DESCRIPTION	IEC STANDRAD
Solar Panels	IEC 61215 IEC 61646 IEC 61724-1
Battery	IEC 61427 IEC 62485
Charge controllers	IEC 62509 IEC 62109-1 IEC 62109-3 IEC 62093 IEC CISPR 11 IEC 61000-4
Inverter	IEC 61683 IEC 62109 IEC 62093 IEC CISPR 11 IEC 61000-4 IEC 61850-7-4
Overall System and Documentation	IEC 60364 IEC 61727 IEC 62446 IEC61200
Others	IEEE 2030.10.2021

Annex A:
Examples of Contractual Commitments

Examples of contractual commitments drawn up by design engineering for the construction of a production unit in a specific location

IMPORTANT NOTE:

Annexes A, B, C, D, E of this standard are given by way of example. The content, although taken from an actual project currently in use, should in no way be copied or taken as a duplicable reference to other situations.

A.1 Execution files and studies

For all of the substations, the Contractor shall provide all of the execution plans prior to the start of the works, and after the picketing visit which will make it possible to record the location of the works.

The execution file will include at least:

- Electrical diagrams of installations and wiring plans.
- Layout plans and detailed civil engineering plans (technical rooms, load-bearing structures, etc.).
- All the calculation notes (calculation of structure and resistance of structures in climatic conditions, calculation of protection and measurement devices, calculation of voltage drops and conductor sections, shading, etc.).
- All component data sheets. The Contractor shall specify for each item of equipment the brand and model proposed, as well as the origin of the equipment (place of manufacture or last major transformation).
- Complete documentation from the manufacturer, for each of the primary components of the solar installations.

The execution file will be submitted to the project team, which will formulate its comments and opinions, and will decide on its completeness, confirming the start of the work.

In general, the execution studies (EXE phase) are entirely the responsibility of the Contractor.

A.2 Acceptance and commissioning

Acceptance of the components delivered will be carried out before installation in the presence of at least one representative of the contracting authority or its agent, and of the Contractor. This reception, organized by the contracting authority, will consist of a visual check of the qualitative and quantitative conformity of the goods delivered with regard to the market.

The Contractor will carry out the works under the supervision of the contracting authority and the project manager.

At the end of the work, a provisional technical acceptance (RTP) will be carried out, it will validate the conformity of the work prior to commissioning followed by the transfer of ownership of the works to the client. The RTP will initiate the full 5-year parts and labor warranty process.

One (01) year after the RTP, a new final technical acceptance (RTD) will record the closing of the market.

Any additional component deemed necessary (and not detailed in this CCTP) by the tenderer will be proposed in the technical brief of the offer.

Under no circumstances may the Contracting Party request a revision of its contract during installation.

In the context of this contract, the involvement of local companies is strongly recommended.

The contract holder undertakes to recruit local staff for unskilled tasks (earthworks, handling, etc.).

Annex B:

Example of Technical Specifications of the main components of PV Power Plants

B.1 Preamble

Particular attention will be paid to the quality of the components offered, the recognized experience of the manufacturers and the feedback from experience of the operation of the components in hot, humid and highly isolated climatic environments.

B.2 General information applicable to all components

B.2.1 Operating conditions

All the requested components are intended to be installed by competent companies in isolated places. However, once installed, these systems will operate in an environment with few qualified personnel. Maximum operational reliability is expected.

B.2.2 Environment and climatic conditions

All the equipment proposed and installed within the framework of this CCTP must imperatively have the constructive characteristics justifying its proven use under the following conditions:

- Ambient temperature: + 10°C to + 45°C
- Relative humidity: up to 100%
- Wind speed: up to 150 km/h (gust) – non-cyclonic zone
- Precipitation: continuous driving rain during the winter period
- Presence of many insects / rodents
- Very high keraunic level (lightning density)

B.2.3 Compatibility between components

Bidders must imperatively ensure the compatibility of connection and operation between the various components, paying particular attention to the following points:

- Supply of compatible PV connectors (must be of the same brand) with the connectors pre-wired on the PV modules and the solar cable supplied, supply of the complete crimping pliers if necessary.

- Supply of PV connectors compatible (must be of the same brand) with the pre-wired connectors at the input of the DC PV boxes (CDC-PV) and the solar cable supplied, supply of the complete crimping pliers if necessary.

- The cable glands and connection terminals of the various DC/AC boxes must be compatible with the cable sections (core and casing) supplied and the nature of the conductors (copper and/or aluminium).

- The PV modules must be strictly identical and interchangeable for all 3 power plants (a single type/brand/power of module for the entire project, excluding solar street lights).

- The supporting structures must be of the same make and model for the 3 sites.

- The synchronous inverters must be of the same brand for all 3 plants.

- The multifunctional converters must be of the same brand for all 3 control units.

- The back-up generators must be of the same brand for all 3 plants.

- All of the components (inverters, converters, DC/AC boxes, TGBT, etc.) are designed for wall mounting on masonry walls and partitions, with a minimum protection index of IP44 to prevent insect intrusion.

B.3 Main plant components

B.3.1 Preamble

The CCTP is based on an electrical architecture and a typology of equipment validated in the APD phase, and provided here for information only.

Tenderers can build their technical offer on the proposed architecture, remaining free to propose any other configuration, in accordance with the technical specifications and the minimum technical requirements.

B.3.2 Photovoltaic modules – common description

- Made from cells based on crystalline silicon (mono or poly),
- Thin film modules are not allowed,
- Glass assembly (minimum 3.2 mm) tedlar or glass rear face (bi-glass modules accepted),
- Composed of 60 or 72 cells of 6” connected in series,
- Peak power under STC conditions greater than or equal to 250 Wp,
- Positive power tolerance,
- The results from the flash tests must be kept available and may be requested upon delivery of the modules,
- Delivered pre-wired with junction boxes containing at least 3 bypass diodes, specific PV plug-in connectors, junction boxes that have never experienced a proven serial fault,
- Anodized aluminum frame,
- Maximum system voltage greater than or equal to 1000 Vdc,
- Class II according to IEC 61140,
- Individual labeling including: manufacturer, model, place of manufacture, electrical characteristics, serial number,
- Manufacturer affiliated with a PV module recycling organization (eg: PV Cycle),
- Compliance with IEC 61215 and IEC 61730-1-2 and CE directives, certified by an approved laboratory
- Power guarantee 90% at 10 years and 80% at 25 years,
- Product warranty greater than or equal to 10 years.

B.3.3 Removable PV connectors

- Unpluggable PV connectors, pre-fitted on components and/or to be supplied by the Contracting Party, male-female assembly to be systematically supplied:

  – Pre-wired on module cable
  – At the end of the chain cables
  – At the input of the DC-PV boxes
  – Minimum characteristics to respect:
  – Rated voltage 1000 Vdc minimum
  – Class II
  – Contact resistance 0.5 Ohms maximum
  – at least IP 65

- Assembly of identical brand connectors exclusively. So-called “compatible” connectors of different brands will not be accepted,

- Compliance with standard NF EN 50521,

- Supply of metal and plastic parts,

B.3.4 PV field supporting structures

- Unit/modular element that can accommodate modules in portrait or landscape position,

- Height of the bottom of the modules from the ground minimum 800 mm,

- 100% aluminum construction and 100% grade 316 stainless steel screws (galvanized steel not permitted),

- Designed for anchoring on concrete foundation such as stringers or studs,

- Inclination and orientation of PV fields to optimize production during the rainy season.

- Supplied with all the fixing parts for the module field, compatible with the modules delivered,

- Drilling for grounding,

- Supplied with the foundation plans (longrine), including reinforcement, as well as the associated calculation notes (to be provided during the EXE phase)

- Device for fixing the modules reducing the risk of theft: PV modules embedded/threaded in specific profiles (eg U-shaped) and end plates fixed with ring nails or equivalent. Equipment based on tamper-proof screws is also allowed (screws to be broken, or with resin).

B.3.5 Synchronous inverters

- Three-phase output + neutral 400 V,

- High efficiency MPPT function (over 99%),

- Compliance with standard IEC 61000-3-2, harmonic distortion coefficient less than 3%

- Yield (euro-eta) greater than 96%

- Compatible in voltage and current with the electrical architecture proposed by the Contractor,

- For each inverter: the nominal power (kVA) will be greater than or equal to 95% of the value of the peak power (kWp) connected to the inverter,

- Wall fixation,

- Designed for operation in high temperature area, minimum IP54

- Minimum warranty of 5 years, extension possible,

- Dynamic screen with display of the main operating characteristics instantaneously and in cumulative value,

- Complies with all the required standards, with possible adjustment of the voltage, frequency and impedance decoupling parameters. These settings of the decoupling protection parameters must be able to be made at any time (not only at commissioning) by the local operators.

- With a wired communication bus for installation in a monitoring device.

B.3.6 Multifunctional converter

- Reversible inverters (charger function in the presence of an AC source: network or generator), IP54

- Maximum power 3 sec @ 25°C minimum 1.5 x Pnom

- Maximum peak current: 2 x Inom

- Nominal battery voltage 48 Vdc / charge algorithm for open lead-acid battery

- Output voltage 230 V pure sine (TDH < 3%), 50 Hz,

- Maximum efficiency greater than 95%, efficiency at 10% of Pnom > 85%,

- Possibility of operation in parallel (master/slave) and in three-phase configuration (from 3 units),

- Different charging modes (absorption, equalization, boost) with configurable voltage threshold, period and duration, temperature compensation

- Relays that can be activated (minimum 2) depending on the battery voltage level (dry contact),

- Voltage thresholds for the different charging modes (absorption, equalization, boost) low battery alarms and protections, with configurable voltage threshold, period and duration,

- Internal protection against short circuits on AC output,

- Reverse polarity protection,

- Overload protection and manual restart (not automatic after fault),

- External temperature sensor for battery temperature measurement (and threshold compensation),

- Calculation of SOC or compatible with addition in the communication bus of a remote battery current measurement shunt, allowing precise knowledge of the battery SOC,

B.3.7 Accumulator battery

- Battery with liquid electrolyte, lead-acid technology, with tubular plate, unit cells of 2V nominal
- Minimum cycling capacity equal to 1500 cycles under a depth of discharge of 70%, (temperature 20°C, discharge rate C100),
- Delivered dry charged, with separate electrolyte
- Transparent plastic container with reading of electrolyte levels on the 4 sides,
- explosion proof caps,
- Set of accessories for electrical connection and protection of live metal parts for an assembly of 24 elements in series (component 1.k), in configuration of 2 rows of 12 elements,
- Capacity, brand and year of manufacture clearly engraved on each element,
- Element filling accessories (hand pump, funnel),
- Densimeter, Gloves, protective glasses, Marking labels, Safety instructions,
- Packing: per unit for connection of 24 elements.
- Support rack (bench)

Annex C:

Examples of wiring specifications and protective devices for installing a mini-grid

C.1 Description of the alarm system and additional protections

- The Contractor will install 2 protection devices against deep discharges, controlled by the 2 relays of the multifunctional converter:

  – A first visual alarm (flashlight type) installed on the roof of the room, will be set to a SOC value or a battery voltage value
  – The second relay will control (opening/closing) the general head circuit breaker, upstream of the 2 network feeders. Its opening/closing will also be controlled by SOC or battery voltage values.

C.1.1 Description of the CDC-PV Box

- The CDC-PV box is located between the PV group and the associated synchronous inverter. Each inverter has its own CDC-PV box, installed in direct proximity to the inverter concerned.

- IP54 PVC box, for wall mounting, with non-padlockable opening front: the switch(es) disconnector(s) of each box must be able to be operated in all circumstances, without the use of tools, in the event of emergency (remote handle on the front permanently accessible).

- Design in accordance with the requirements of the UTE 15-712-1 guide, July 2013

- Internal wiring with PV cable (see below) only

- Electrical architecture:
  – inputs (+ and -) for PV strings (V_{co} max = V_{co} STC * 1.1) / (I_{dc} in max = I_{sc} STC * 1.25), removable PV connector base,
  – paralleling of strings if necessary,
  – cable gland outputs for solar cable to inverters,
  – fuse protection of reverse currents if applicable (see guide UTE C15-712-1), if the value of the reverse current (Ir) of the modules and the number of strings in parallel justify it.
  – **No split ducting in the box (2 cables in parallel per ducting prohibited)**
- Characteristics of breaking and protection equipment:
  – Disconnect switches: disconnection of the entire PV group associated with each tracker of the inverter (if double tracker inverter, 2 disconnect switches, or a single one that can disconnect the 2 trackers)
  – Implementation of surge arresters downstream of the switch disconnectors,
  – Type 2 PV surge arresters compliant with standard NF EN 50539-11, (with surge arrester indicator in good condition),
  – Replacement surge arrester cartridges (1 unit per box),
  – GPV fuse, if the Ir current of the modules and the number of strings in parallel justify it according to UTE C15-712-1, including spare fuses (2 per cabinet),

- Safety labeling in accordance with the UTE C15-712-1 guide.

C.1.2 AC bus main switch – description

- The ACTGBT will group together all the AC outputs of the synchronous inverters, the generator set, the inputs (AC in) and outputs (AC out) of the multifunctional converters, the network power supply outlet. It will act as AC BUS.

- PVC box or IP54 metal cabinet, for wall mounting, with door that can be opened with a handle, general cut-off offset on the front (the cabinet can be opened under load), ventilation grille.

- Electrical architecture:

  – Arrivals in the lower part of the box, by cable gland for flexible multi-strand HO7 RNF cable (see type and section below)
  – Cable protection by curve C circuit breakers or fuses (phase protection, without breaking the neutral). The rated current of the circuit breakers will be in accordance with the section of the protected conductor, and greater than or equal to 1.4 times the maximum transit current in the associated nominal regime, to limit the risks of overheating.
  – General circuit breaker at the head, controllable (opening/closing) by the relays of the multifunctional converter
  – Type 2 AC surge protection
  – 4-pole transfer switch
  – General network meter (electronic or mechanical display)
  – Separate outlet for local power supply (auxiliary) – see Figure 11

- As proposed in the block diagram attached in the appendix, the network feeder will be split to accommodate 2 (GPV1 and GPV2) or 3 (GPV3) feeders, each equipped with their own disconnect switch.

- The 2 or 3 network outlets will be made with screw terminal blocks (cage terminal blocks prohibited) allowing electrical connection to the busbar protected using tubular lugs crimped into the single-pole cables intended for the network. (NB for reasons of space and functionality, this function can be performed in a second cabinet nearby).

C.1.3 CDC-BAT battery box

- PVC box or IP54 metal cabinet, for wall mounting, with door that can be opened with a handle, general cut-off offset on the front (the cabinet can be opened under load), ventilation grille.

- Box containing fuses (Gg) and disconnect switches (direct current specific), complying with the rules for the protection of persons and property proposed in the appended diagrams.

- Input and output connection on busbar only, with crimped terminal.

- Cable glands compatible with single-core HO7 RNF cable with cross-section between 1x70 mm^2 and 1x120 mm^2

C.2 Description of the main pipelines

NB 1: in all cases, the TGBT will fulfill at least the functions of protection of persons and property

NB2: the TGBT of GPV1 and GPV2 will be identical.

NB3: for GPV3, a design with remote relay and multi-source coupling on a single bus is strongly recommended.

NB4: If all the functions requested for the TGBT are not compatible in a single cabinet, the Contracting Party may outsource the associated functions in annex cabinets/cabinets (for example: the outgoing protection board for the auxiliary power supply, the source inverter, multiple network feeders, additional protection of the generating set, the possible coupling of several synchronous inverters, etc.). Each cable connecting the TGBT to the annex cabinet must be protected at the input by a suitable circuit breaker/fuse.

C.2.1 DC – PV trunking
- Identification: PV-CDC PV field – synchronous inverter
- Solar Cable, Single Core, Double Insulated, Class II
- Compliance with UTE C32-502 guide,
- Maximum core operating temperature: 120°C,
- DC voltage withstand: 0.9/1.8 kV,
- Black color,
- Marking on the cable: brand and technical characteristics,

C.2.2 AC cabling: Inverter / TGBT
- HO7 RNF copper cable (flexible), 5GX.
- Complies with EN 50525-2-21
- Operating voltage 0.6/1 kV

C.2.3 AC trunking: Multifunctional converter / TGBT
- HO7 RNF copper cable (flexible), 5GX.
- Complies with EN 50525-2-21
- Operating voltage 0.6/1 kV

C.2.4 DC cabling: Multifunctional converter / CDC BAT
- HO7 RNF copper cable (flexible), unipolar
- Complies with EN 50525-2-21
- Operating voltage 0.6/1 kV

C.2.5 DC cabling: CDC BAT / BATTERY
- HO7 RNF copper cable (flexible), unipolar
- Complies with EN 50525-2-21
- Operating voltage 0.6/1 kV

C.2.6 Equipotential bonding cable / protective conductor
- Single-pole HO5 V/K (flexible) copper cable / minimum section 16mm2 for all equipotential and earthing connections
- Complies with the NFC 32-201 standard

C.2.7 Other conduit/wire ways between TGBT and any ancillary boxes
- If, to fulfill all the functions required of the TGBT, additional boxes/cabinets are envisaged, the Contractor is free to propose ACs of the HO7 RNF or 1000 R2V type.

C.2.8 Labeling / marking
- The Contractor will implement labeling/marking on each of the components that is extremely clear, long-lasting (rigid engraved plates) and consistent with the DOE and DEM. The labeling must be as complete and explicit as possible.
- Full safety signage will also be displayed.

C.2.9 Safety equipment

- In addition to the PPE provided for handling the batteries, the Contractor shall install 1 fire extinguisher in each power plant (class E gas fire extinguisher), i.e. a total of 3 fire extinguishers.

C.2.10 Monitoring – description

- Each hybrid plant will be equipped with unique (centralised) monitoring equipment. The so-called "monitoring" assembly must make it possible to respond, at least, to 3 functions:
  - Real-time display of the main instantaneous operating data of the PV plant, at least:
    - Time, date
    - DC side operating characteristics,
    - AC side operating characteristics,
    - Daily energy distributed, in kWh
    - Total cumulative energy produced since commissioning, in kWh (MWh),
  - Recording on external medium (SD card or USB key) of the main UPS operating data, in maximum steps of 15 minutes, with a minimum storage autonomy of 1 year.

- All monitoring must be carried out by RS485 bus (no Wifi or Bluetooth communication), which must integrate all the components (synchronous inverters, multifunctional converters, shunt/external relay if necessary).

- The monitoring unit will be powered by the electrical network via the dedicated auxiliary power supply.

- The monitoring system must have a screen. If this is not the case, the Contractor will provide the PC or tablet needed to read the information from the system.

- The Contractor shall provide all the RS485 cables and RJ45 connectors necessary for the complete implementation of the monitoring system for each plant.

- The monitoring will be delivered with remote monitoring equipment by aerial telecommunications (local GSM DATA network), including GSM modem, supply and commissioning. The required DATA subscription will be paid for, the first year of operation (between the 2 receptions) by the Contractor. The data sent must be usable on an online platform (type of monitoring platform for inverter manufacturers), accessible from a computer connected to the Internet, free of charge. Bidders are invited to find out in advance about the feasibility and cost of data subscription in the local context, and to inform their offer of any limits and risks.

Annex D:

Synthesis of lightning protection devices for photovoltaic mini-grids

D.1 General operating principle

The surge arrester is a device intended to limit the level of overvoltages (for example of atmospheric origin) transmitted by the cables to a level compatible with the impulse withstand voltage of the equipment of the installation and of the equipment powered by this installation.

It is generally placed between each active conductor and the mass of the equipment, itself connected to the earth, and sometimes between active conductors.

A surge arrester, installed between active conductors and ground, protects the insulation.

A surge arrester, installed between active conductors, protects the equipment.

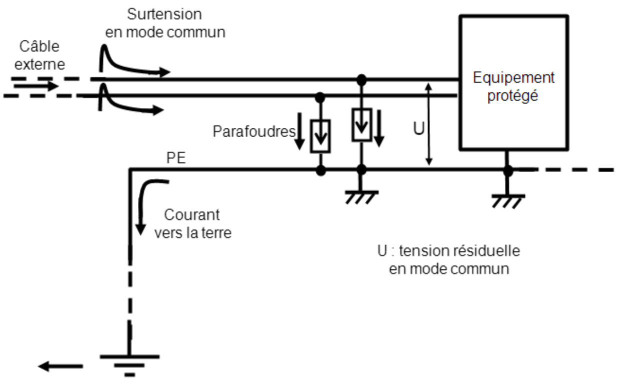


Figure D.1: The common mode current which passes through the surge arresters closes through the earth

Under normal voltage, the arrester behaves almost like an infinite resistor and the current flowing through it is zero or negligible.

On the other hand, on the appearance of an overvoltage, as soon as the voltage at the terminals of the surge arrester exceeds a certain threshold, the surge arrester becomes conductive, letting a current flow, which limits the voltage at its terminals, therefore at the terminals of the device to be protected.

For each use case, the arrester is chosen mainly according to the following parameters:

- U_c: Maximum operating voltage at the SPD terminals
- Protection level: U_p , which must belower than the permissible overvoltage by the devices to be protected: Uw (data provided by the manufacturer)
- IMP or In: intensity of the current that the surge arrester will have to withstand during the overvoltage duration
- Withstand and behavior against short-circuit currents
- Behavior at end of life or short circuit

D.2 The characteristics of a surge arrester

To respond to the protection of various overvoltages due to lightning, 2 types of standardized pulses have been defined according to standard IEC 61643-11:

- Type 1: 10/350 µs test pulse, this conventional wave comes closest to the direct lightning current wave.
- Type 2: 8/20 µs test pulse, this wave is the closest to current waves due to the indirect effects of lightning.

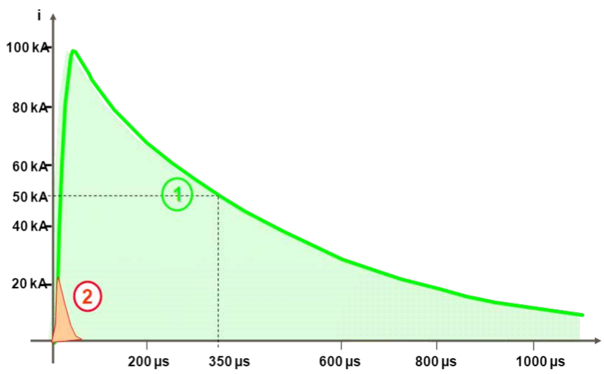


Figure D.2. Normalized impulses of the 2 types of lightning current wave.

For each normalized pulse 1 or 2, a surge arrester has been defined whose characteristics are described below.

D.2.1 Type 1 AC surge arrester

– Protection corresponding to 10/350 µs pulses

– Head surge arrester recommended for the protection of equipment subject to overvoltage from a direct lightning strike or at risk of maximum lightning current, such as structures equipped with lightning rods or overhead network power supply when the lightning strike occurs on the last staff.

– Placed at the line inputs in the main TGBT of a site subject to a high lightning risk

– Main parameters:

  – I_{imp}: Impulse current defined by the peak current and the load Q
  – U_p: Protection level (peak voltage at the SPD terminals during the passage of the rated discharge current)
  – U_c: Operating voltage
  – Disconnection type at end of life

D.2.2 Type 2 AC surge arrester

– Protection corresponding to 8/20 µs pulses

– General purpose arrester recommended for locations relatively exposed but not subject to direct lightning current

– Placed at the entrances of the LV lines in buildings if the risk of direct shock current is low, but also and above all in the divisional distributions in addition to the main surge arrester.

Main parameters:

  – I_n: rated/discharge current (peak value of 8/20 µs waveform current that the arrester can sink 15 times)
  – U_p: Protection level (peak voltage at the SPD terminals during the passage of the rated discharge current)
  – U_c: Maximum voltage in steady state at the terminals of the surge arrester without affecting its operation
  – Disconnection type at end of life

The designation T1+2 surge arrester usually means that the type 1 surge arrester has a wave flow capacity (10/350 µs) and above all a level of protection U_p equivalent to coordination between a type 1 surge arrester and type 2, inferior to holding electronic equipment.

D.3 Surge protection for direct current circuits in the low voltage range (photovoltaic circuits)

As for the AC part, type 1 and 2 surge protectors exist, specifically designed for direct current operation on the one hand, and adapted to the electrical specificities of photovoltaic generators on the other.

To make the right choice of DC and AC surge protectors in a photovoltaic installation, it is useful to refer to the indications of the CLC TS 51643-32 or IEC 61643-32 and IEC 61643-12 standards to determine the possible PV surge protectors and fuses suitable for photovoltaic installations. .

The specific characteristics of the DC PV surge arrester are determined by the following criteria, in accordance with the IEC 60364-7-712 standard:

– I_n: nominal discharge current greater than or equal to 5 kA in 8/20 wave µs

– I_{imp}: Impulse current in wave10/350µscharacterizing type 1 surge arresters.

ISCPW: short-circuit current withstand of a surge arrester. The surge arrester and its disconnector (internal or external) must have an ISCPW current greater than the Iscmax of the PV generator. A surge arrester with an internal disconnector must also interrupt the short-circuit current generated by the battery. Otherwise, an external disconnector specified by the manufacturer must be installed.

– U_{CPV}: maximum steady state voltage of a photovoltaic surge arrester dedicated to protecting the DC part of the PV generator (the voltage must be chosen so that the surge arrester does not conduct open circuit voltage of the modules in the worst conditions; in practice, we take U_{CPV} > UOC_MAX, the open circuit voltage value per 1000 W/m^2 and in the coldest conditions.

– U_p: level of protection depending on the devices to be protected. In accordance with standard IEC 60364-7-712:2017, U_p must be lower than the impulse withstand voltage U_w of the devices and circuits to be protected. In practice, it is often recommended to maintain a safety margin of at least 20% between the voltage withstand value of the equipment U_w and U_p.

NOTE: For photovoltaic installations, the table below, which is taken from the international standard IEC 61643-32, gives indications of UW values, if this information is not stipulated by the manufacturers of inverters or other equipment

UOC, MAX (V)	Uw (V)			
	PV module Class B basic insulation	Inverter	Other equipment	Class A PV module and other equipment with double/reinforced insulation
100	800	≥2500	800	1500
150	1500		1500	2500
300	2500		2500	4000
424	4000		4000	4000
600		4000	4000	6000
800	5000		5000	6000
849	6000		6000	8000
1000	6000	6000	6000	8000
1500	8000	8000	8000	12000

Table D.1: Uw Values according to IEC 61643-32.

The U_p voltage of the external surge protectors must be coordinated with the characteristics of the devices integrated in the PV controllers and inverters to be protected. Manufacturers must then provide the data necessary for the selection of surge arresters. These surge protectors must comply with IEC standards61643-31 and IEC 61643-11

StandardIEC 61643-31 for surge arresters installed on the DC part of the PV generator

the IEC 61643-11 standard for surge arresters installed on the AC part of the installation

Figure D.3: Examples of Type 2 Dc PV surge arrester

D.4 Installation of surge arresters

Surge arresters are generally installed on all lines entering or leaving the site housing the equipment to be protected (in practice for mini-grids: the photovoltaic field and the components of the technical room).

A single surge arrester can protect the entire installation, on the same line, if the length of the pipe between the surge arrester and the furthest equipment is less than 10 m. Otherwise, surge arresters should be installed at each end of the link.

The mounting of surge arresters depends on the ground connection diagram of the installation, there are thus two types of protection:

– Common mode: protection between active conductors and earth

– Differential mode: protection between active conductors (between phase and neutral or between positive and negative polarity)

On the other hand, for lightning protection to be effective, the connections between the surge arrester and the active conductors and the earth terminal must be as short as possible (< 50cm), the impedance of these connections reducing the protection provided by the surge arrester by increasing the voltage across the terminals of the device to be protected in the event of a lightning current.

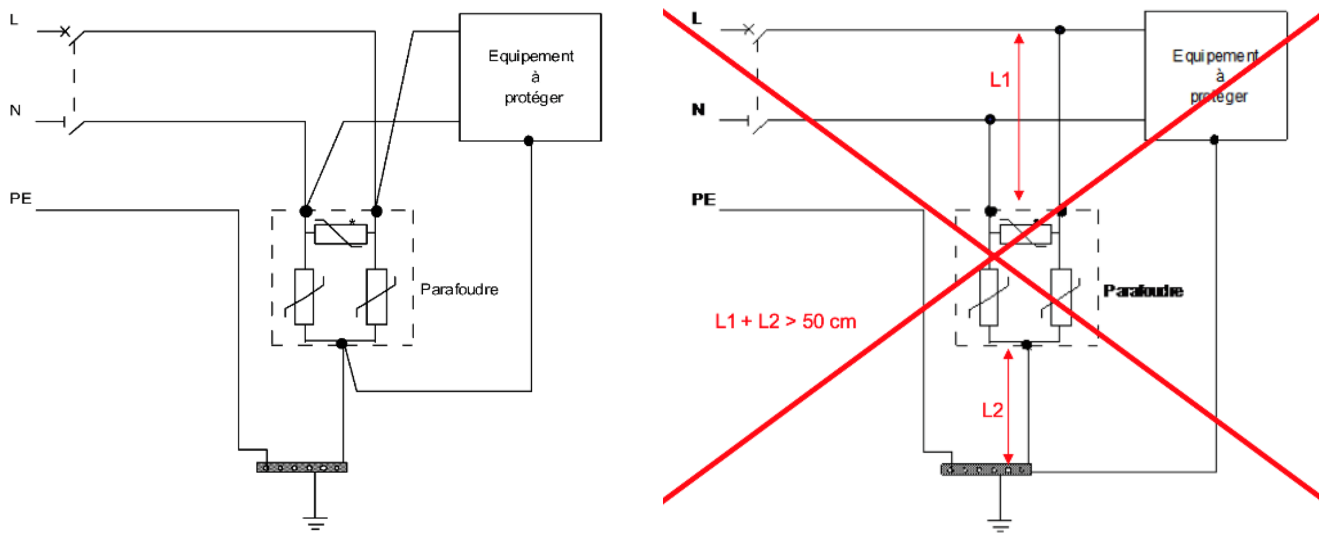


Figure D.4: Rule known as "50cm" for the implementation of surge arresters.

D.5 Decommissioning the arrester at the end of its life

The elements used in the construction of surge arresters are likely to deteriorate by slow aging of its components causing thermal or sudden runaway by short-circuiting. So that this does not endanger the circuit and operating safety, it is necessary to provide protection leading to its disconnection:

– either by internal thermal disconnection system (with the exception of spark gaps without risk of thermal runaway)

– either by circuit breaker or fuses upstream of the surge arrester,

When the cut-out device putting the surge arrester out of service has operated, the protection against overvoltages is no longer ensured and the surge arrester must be replaced. The user must be informed of the situation by the operation of a visual signal or by remote transmission. Some surge arresters have a device reflecting the state of the surge arrester and allowing it to be replaced before its lifespan in order to ensure continuity of protection.

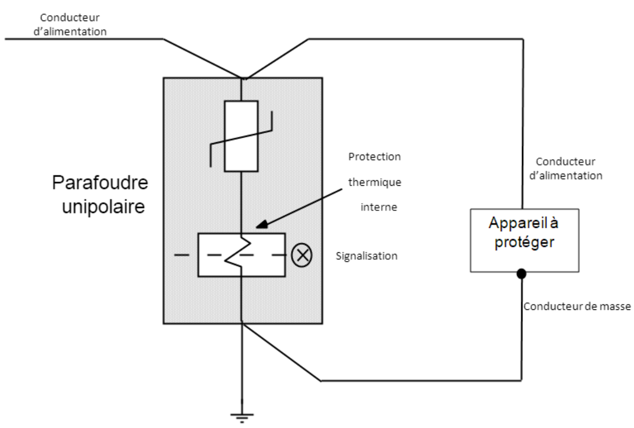


Figure D.5. Example of decommissioning a faulty SPD by internal thermal protection

Annex E:

Synthesis of lightning protection devices for photovoltaic mini-grids

The main lightning risks of an autonomous and/or hybrid photovoltaic production system concern the following points:

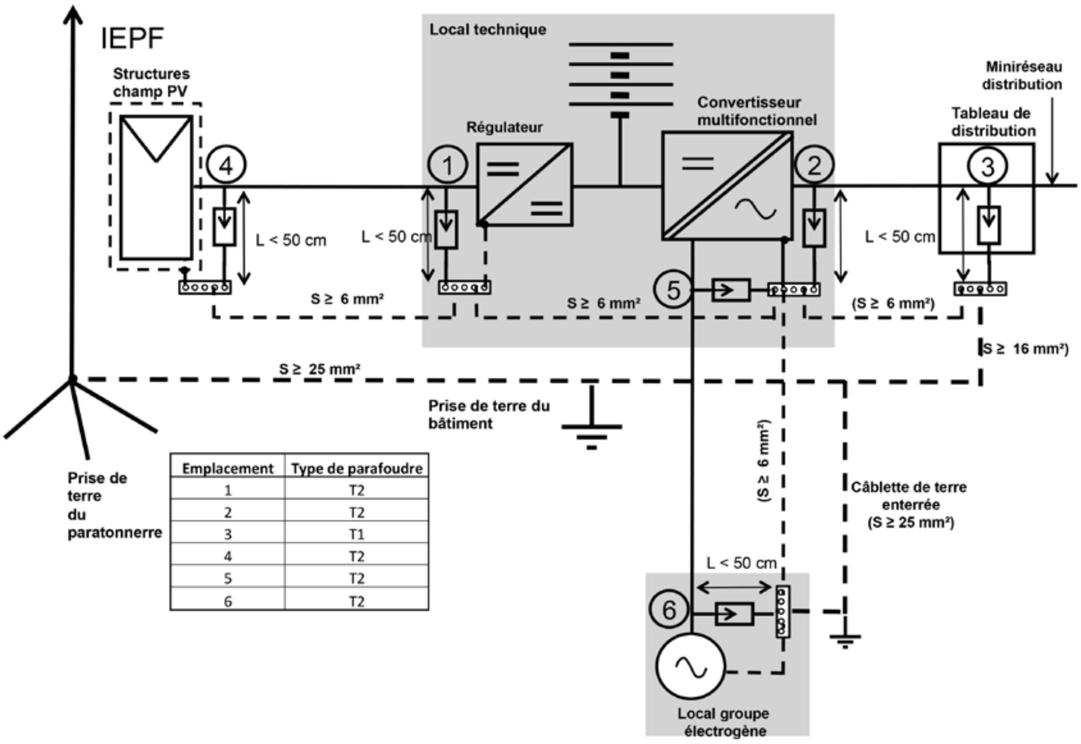
– Complete destruction by lightning impact on the installation (direct lightning strike)

– Overvoltages carried by the electrical conductors (including the equipotential bonding conductors), coming from the main pipes (between the PV field and the technical room, between the generator set and the technical room, and most often, coming from the distribution network). These temporary overvoltages can lead to:

– The destruction of photovoltaic modules,
– The destruction of the generating set, if applicable
– The destruction of electronic components: inverters, chargers, converters, batteries.

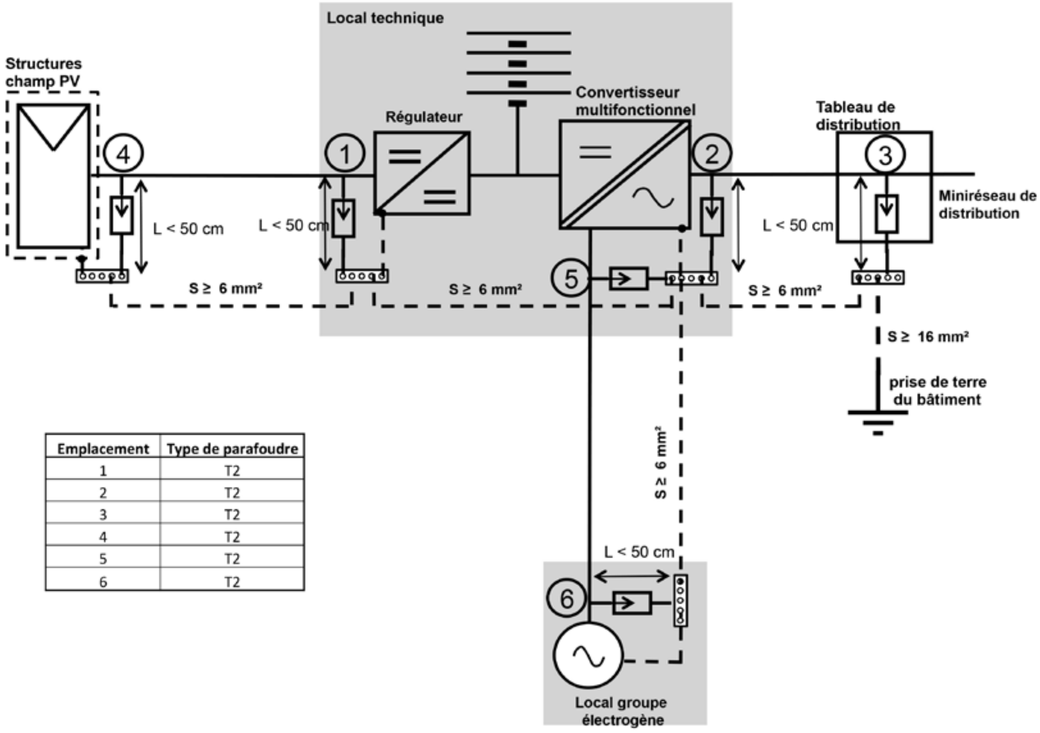
The diagrams and table below summarize the principles for implementing lightning protection devices (SPF) for installations with and without IEPF.

The standard recommends connecting the ground network of the PV installation to the ground connection of the IEPF if the shortest distance between the 2 is less than the separation distance “s” as defined in standard IEC 62350- 3.



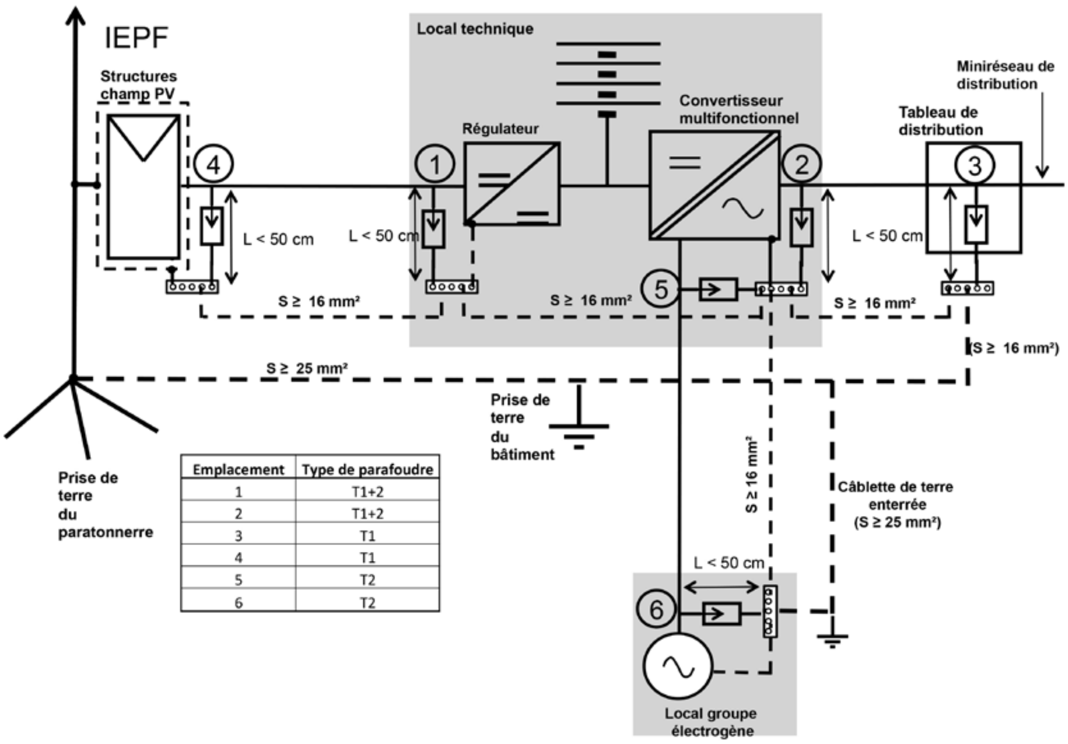
Emplacement	Type de parafoudre
1	T2
2	T2
3	T1
4	T2
5	T2
6	T2

Figure E.1: Example: Implementation of surge protectors within a stand-alone hybrid installation without IEPF. If there is a PV inverter on the AC bus, surge arresters on the DC-PV side and AC side must be implemented to protect the inverter.



Emplacement	Type de parafoudre
1	T2
2	T2
3	T2
4	T2
5	T2
6	T2

Figure E.2: Example: Implementation of surge arresters in a stand-alone hybrid installation with IEPF and compliance with the separation distance (the down conductor and the ground are not connected).If there is a PV inverter on the AC bus, surge arresters on the DC-PV side and AC side must be implemented to protect the inverter.



Emplacement	Type de parafoudre
1	T1+2
2	T1+2
3	T1
4	T1
5	T2
6	T2

Figure E.3: Example: Implementation of surge protectors in a stand-alone hybrid installation with non-insulated IEPF (the down conductor and the ground are connected). If there is a PV inverter on the AC bus, surge arresters on the DC-PV side and AC side must be implemented to protect the inverter.

Installation		DC SIDE		AC SIDE			
		PV Module – PV Controller or Inverter		Converter - GE		Converter - TGBT	
Location of lightning arresters		4 1	4 1	6 5	6 5	2 3	2 3
Distance between arresters		< 10m	> 10m	< 10m	> 10m	< 10m	> 10m
With IEPF	Uninsulated SPF UP < UW	T1 T1+2	T1 T1+2	T1 T1+2	T1 T1+2	T1+2 T1	T1+2 T1
	SPF Isolated 50% UW < UP < UW	- T2	T2 T2	T1 T1+2	T1 T1+2	T1+2 T1	T1+2 T1
	SPF Isolated UP < 50% UW	- T2	- T2	- T2	T2 T2	T2 T1	T2 T1
Without IEPF	50% UW < UP < UW	- T2	T2 T2	- T2	T2 T2	- T2	T2 T2
	UP < 50% UW	- T2	- T2	- T2	- T2	- T2	- T2

Table E.1: Summary table that specifies the type of surge arrester to be installed in each case.

Bibliography

For energy staorage the following series of documents should be considered :

1. Electrical energy storage (EES) systems - Part 1: Vocabulary

2. Electrical energy storage (EES) systems - Part 2-1: Unit parameters and testing methods - General specification

3. Electrical energy storage (EES) systems - Part 2-2: Unit parameters and testing methods - Application and performance testing

4. Electrical energy storage (EES) systems - Part 2-200: Unit parameters and testing methods - Case study of electrical energy storage (EES) systems located in EV charging station with PV

5. Electrical energy storage (EES) systems - Part 3-1: Planning and performance assessment of electrical energy storage systems - General specification

6. Electrical energy storage (EES) systems - Part 3-2: Planning and performance assessment of electrical energy storage systems - Additional requirements for power intensive and renewable energy sources integration related applications

7. Electrical energy storage (EES) systems - Part 3-3: Planning and performance assessment of electrical energy storage systems - Additional requirements for energy intensive and backup power applications

8. Electrical energy storage (EES) systems - Part 4-1: Guidance on environmental issues - General specification

9. Electrical energy storage (EES) systems - Part 5-1: Safety considerations for grid-integrated EES systems - General specification

10. Electrical energy storage (EES) systems - Part 5-2: Safety requirements for grid-integrated EES systems - Electrochemical-based systems

11. Electrical energy storage (EES) systems - Part 5-3: Safety requirements for grid-integrated EES systems – Performing unplanned modification of electrochemical based system

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