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TECHNICAL SPECIFICATION

colour inside

Ground-mounted photovoltaic power plants – Design guidelines and recommendations

IEC TS 62738:2018-08(en)

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INTERNATIONAL
ELECTROTECHNICAL
COMMISSION

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

GROUND-MOUNTED PHOTOVOLTAIC POWER PLANTS – DESIGN GUIDELINES AND RECOMMENDATIONS

FOREWORD

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- the subject is still under technical development or where, for any other reason, there is the future but no immediate possibility of an agreement on an International Standard.

Technical specifications are subject to review within three years of publication to decide whether they can be transformed into International Standards.

IEC TS 62738, which is a technical specification, has been prepared by IEC technical committee 82: Solar photovoltaic energy systems.

The text of this technical specification is based on the following documents:

Enquiry draft	Report on voting
82/1291/DTS	82/1374/RVDTS

Full information on the voting for the approval of this technical specification can be found in the report on voting indicated in the above table.

This document has been drafted in accordance with the ISO/IEC Directives, Part 2.

The committee has decided that the contents of this publication will remain unchanged until the stability date indicated on the IEC website under "http://webstore.iec.ch" in the data related to the specific publication. At this date, the publication will be

- transformed into an International standard,
- reconfirmed,
- withdrawn,
- replaced by a revised edition, or
- amended.

A bilingual version of this publication may be issued at a later date.

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INTRODUCTION

This document sets out general guidelines and recommendations for the design and installation of utility scale ground-mounted photovoltaic (PV) power plants. The focus is largely on design aspects that differ from those of conventional residential and commercial PV systems. Power plants are a significant and growing component of the PV market, yet design methodologies range considerably, partly due to the fact that systems are not accessible to the public or non-qualified personnel. Overall guidelines are still needed to ensure safe, reliable, and productive systems.

GROUND-MOUNTED PHOTOVOLTAIC POWER PLANTS – DESIGN GUIDELINES AND RECOMMENDATIONS

1 Scope

This document sets out general guidelines and recommendations for the design and installation of ground-mounted photovoltaic (PV) power plants. A PV power plant is defined within this document as a grid-connected, ground-mounted system comprising multiple PV arrays and interconnected directly to a utility's medium voltage or high voltage grid. Additional criteria is that PV power plants are restricted from access by non-qualified persons and are continuously monitored for safety and protection, either by on-site personnel or by active remote monitoring. Technical areas addressed are those that largely distinguish PV power plants from smaller, more conventional installations, including ground mounted array configurations, cable routing methods, cable selection, overcurrent protection strategies, equipotential bonding over large geographical areas, and equipment considerations.

Safety and design requirements are referenced to the applicable requirements of IEC 62548 to address distinct differences relative to the design requirements for residential, commercial and other non-power plant applications. In general, existing standards are referenced wherever possible for uniformity. Emphasis is placed on systems employing d.c. string based systems using large scale central inverters or 3-phase string inverters, but relevant sections are also applicable to systems employing a.c. modules or d.c./d.c. converters. Medium voltage transformers, switchgear, collection systems, substations, utility interconnection, auxiliary loads, energy storage systems, and communication services are addressed, but discussion is mostly limited to recommended references to other standards and requirements.

Rooftop-mounted systems, building integrated PV (BIPV) and building applied PV (BAPV) are not included in the scope of this document. The principles of restricted-access power plants are not compatible with systems on buildings, which are used for purposes other than power generation.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC 60076-1, *Power transformers – Part 1: General*

IEC 60076-2, *Power transformers – Part 2: Temperature rise for liquid-immersed transformers*

IEC 60076-3, *Power transformers – Part 3: Insulation levels, dielectric tests and external clearances in air*

IEC 60076-4, *Power transformers – Part 4: Guide to the lightning impulse and switching impulse testing – Power transformers and reactors*

IEC 60076-5, *Power transformers – Part 5: Ability to withstand short-circuit*

IEC 60076-7, *Power transformers – Part 7: Loading guide for mineral-oil-immersed power transformers*

IEC 60085, *Electrical insulation – Thermal evaluation and designation*

IEC 60137, *Insulated bushings for alternating voltages above 1000 V*

IEC 60183, *Guidance for the selection of high-voltage A.C. cable systems*

IEC 60228, *Conductors of insulated cables*

IEC 60255-21-3, *Electrical relays – Part 21: Vibration, shock, bump and seismic tests on measuring relays and protection equipment – Section 3: Seismic tests*

IEC 60296, *Fluids for electrotechnical applications – Unused mineral insulating oils for transformers and switchgear*

IEC 60364-5-52, *Low-voltage electrical installations – Part 5-52: Selection and erection of electrical equipment – Wiring systems*

IEC 60364-5-54, *Low-voltage electrical installations – Part 5-54: Selection and erection of electrical equipment – Earthing arrangements and protective conductors*

IEC 60502-1, *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 60502-2, *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 2: Cables for rated voltages from 6 kV (Um = 7,2 kV) up to 30 kV (Um = 36 kV)*

IEC 60853 (all parts), *Calculation of the cyclic and emergency current rating of cables*

IEC 60870-5-104, *Telecontrol equipment and systems – Part 5-104: Transmission protocols – Network access for IEC 60870-5-101 using standard transport profiles*

IEC TR 60890, *A method of temperature-rise verification of low-voltage switchgear and controlgear assemblies by calculation*

IEC 60947-3:2008, *Low-voltage switchgear and controlgear – Part 3: Switches, disconnectors, switch-disconnectors and fuse-combination units*

IEC 60947-3:2008/AMD1:2012
IEC 60947-3:2008/AMD2:2015

IEC 61000-4-2, *Electromagnetic compatibility (EMC) – Part 4-2: Testing and measurement techniques – Electrostatic discharge immunity test*

IEC 61215-2, *Terrestrial photovoltaic (PV) modules – Design qualification and type approval – Part 2: Test procedures*

IEC 61238-1 (all parts), *Compression and mechanical connectors for power cables*

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

IEC 61439-1, *Low-voltage switchgear and controlgear assemblies – Part 1: General rules*

IEC 61439-2, *Low-voltage switchgear and controlgear assemblies – Part 2: Power switchgear and controlgear assemblies*

IEC 61643-32, *Low-voltage surge protective devices – Part 32: Surge protective devices connected to the d.c. side of photovoltaic installations – Selection and application principles*

IEC 61724-1, *Photovoltaic system performance – Part 1: Monitoring*

IEC TS 61724-2, *Photovoltaic system performance – Part 2: Capacity evaluation method*

IEC TS 61724-3, *Photovoltaic system performance – Part 3: Energy evaluation method*

IEC 61850 (all parts), *Communication networks and systems for power utility automation*

IEC 61936-1, *Power installations exceeding 1 kV a.c. – Part 1: Common rules*

IEC 62109-1, *Safety of power converters for use in photovoltaic power systems – Part 1: General requirements*

IEC 62109-2, *Safety of power converters for use in photovoltaic power systems – Part 2: Particular requirements for inverters*

IEC 62271-1, *High-voltage switchgear and controlgear – Part 1: Common specifications for alternating current switchgear and controlgear*

IEC 62271-100, *High-voltage switchgear and controlgear – Part 100: Alternating current circuit-breakers*

IEC 62271-102, *High-voltage switchgear and controlgear – Part 102: Alternating current disconnectors and earthing switches*

IEC 62271-103, *High-voltage switchgear and controlgear – Part 103: Switches for rated voltages above 1 kV up to and including 52 kV*

IEC 62271-200, *High-voltage switchgear and controlgear – Part 200: AC metal-enclosed switchgear and controlgear for rated voltages above 1 kV and up to and including 52 kV*

IEC TS 62271-210, *High-voltage switchgear and controlgear – Part 210: Seismic qualification for metal enclosed and solid-insulation enclosed switchgear and controlgear assemblies for rated voltages above 1 kV and up to and including 52 kV*

IEC TR 62271-300, *High-voltage switchgear and controlgear – Part 300: Seismic qualification of alternating current circuit-breakers*

IEC 62305-2, *Protection against lightning – Part 2: Risk management*

IEC 62446-1, *Photovoltaic (PV) systems – Requirements for testing, documentation and maintenance – Part 1: Grid connected systems – Documentation, commissioning tests and inspection*

IEC 62446-2, *Photovoltaic (PV) systems – Requirements for testing, documentation and maintenance – Part 2: Grid connected systems – Maintenance of PV systems* (to be published)

IEC 62548:2016, *Photovoltaic (PV) arrays – Design requirements*

IEC 62817, *Photovoltaic systems – Design qualification of solar trackers*

IEC 62852, *Connectors for DC-application in photovoltaic systems – Safety requirements and tests*

EN 50539-11, *Low-voltage surge protective devices – Surge protective devices for specific application including d.c. – Part 11: Requirements and tests for SPDs in photovoltaic applications*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in IEC 62548 as well as the following apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

- IEC Electropedia: available at http://www.electropedia.org/
- ISO Online browsing platform: available at http://www.iso.org/obp

3.1
PV power plant
grid-connected, ground-mounted PV system comprising multiple PV arrays and interconnected directly to a utility's medium voltage or high voltage grid

Note 1 to entry: Additional criteria are that PV power plants are restricted from access by non-qualified personnel and are continuously monitored for safety and protection, either by on-site personnel or by active remote monitoring.

3.2
electrically skilled person
person with relevant education and experience to enable him or her to perceive risks and to avoid hazards which electricity can create

3.3
electrically instructed person
person adequately advised or supervised by electrically skilled persons to enable him or her to perceive risks and to avoid hazards which electricity can create

3.4
ordinary person
person who is neither a skilled person nor an instructed person

3.5
string wiring harness
cable assembly that aggregates the output of multiple PV string conductors along a single main conductor

Note 1 to entry: The harness may or may not include fusing on the individual string conductors. The wiring harness typically does not include a disconnect device in line.

4 Compliance with IEC 62548

The design, erection and verification of PV power plants as defined in this document should generally comply with the requirements of IEC 62548 and its references to the IEC 60364 series.

Specific exceptions and variations to the requirements of IEC 62548 called out in this document are permissible due to the restricted access conditions placed on PV power plants.

5 PV array system configuration

5.1 General

This clause discusses PV array earthing, control, layout and mechanical configurations found in PV power plants.

5.2 Earthing configurations

5.2.1 General

Considerations for earthing a PV array are addressed in this clause. The requirements of manufacturers of PV modules and manufacturers of power conversion equipment (PCE) to which the PV array is connected shall be taken into account in determining the allowable or required system earthing arrangements.

5.2.2 Use of un-earthed d.c. circuits

When installed with a residual current monitoring system and/or with isolation resistance detection, PV systems with un-earthed d.c. arrays offer robust earth fault protection. A failure in any cable (positive or negative), causing a short circuit from the cable to an earthed surface results only in a shift of the array voltage reference from a floating state to an earth-referenced state. It does not create a closed circuit for fault current to flow, and therefore does not present a fire hazard. Un-earthed d.c. circuits are also a requirement where simple separation or isolation from an earthed a.c. system is not provided by the inverter or a transformer.

5.2.3 Use of high-ohmic earthed d.c. circuits

High-ohmic earthed systems may be used in plants where operators want to achieve some of the benefits of an un-earthed or floating system while still maintaining an array voltage reference to ground to prevent potential induced degradation (PID). Resistance values are set to limit fault current to a target level (below 300 mA for example) in case of a hard fault occurring on the unreferenced d.c. circuit pole. This significantly reduces the arcing and fire causing currents that can occur with grounded systems, specifically those without supplemental high-sensitive ground fault detection.

5.2.4 Use of functionally earthed d.c. circuits

Protective earthing of any of the conductors of the PV array is not permitted. Earthing of one of the conductors of the PV array for functional reasons is allowed through internal connections inherent in the PCE or other earth fault protective device if designed and qualified for this configuration. Functionally earthed d.c. array based systems are sometimes used to prevent module PID.

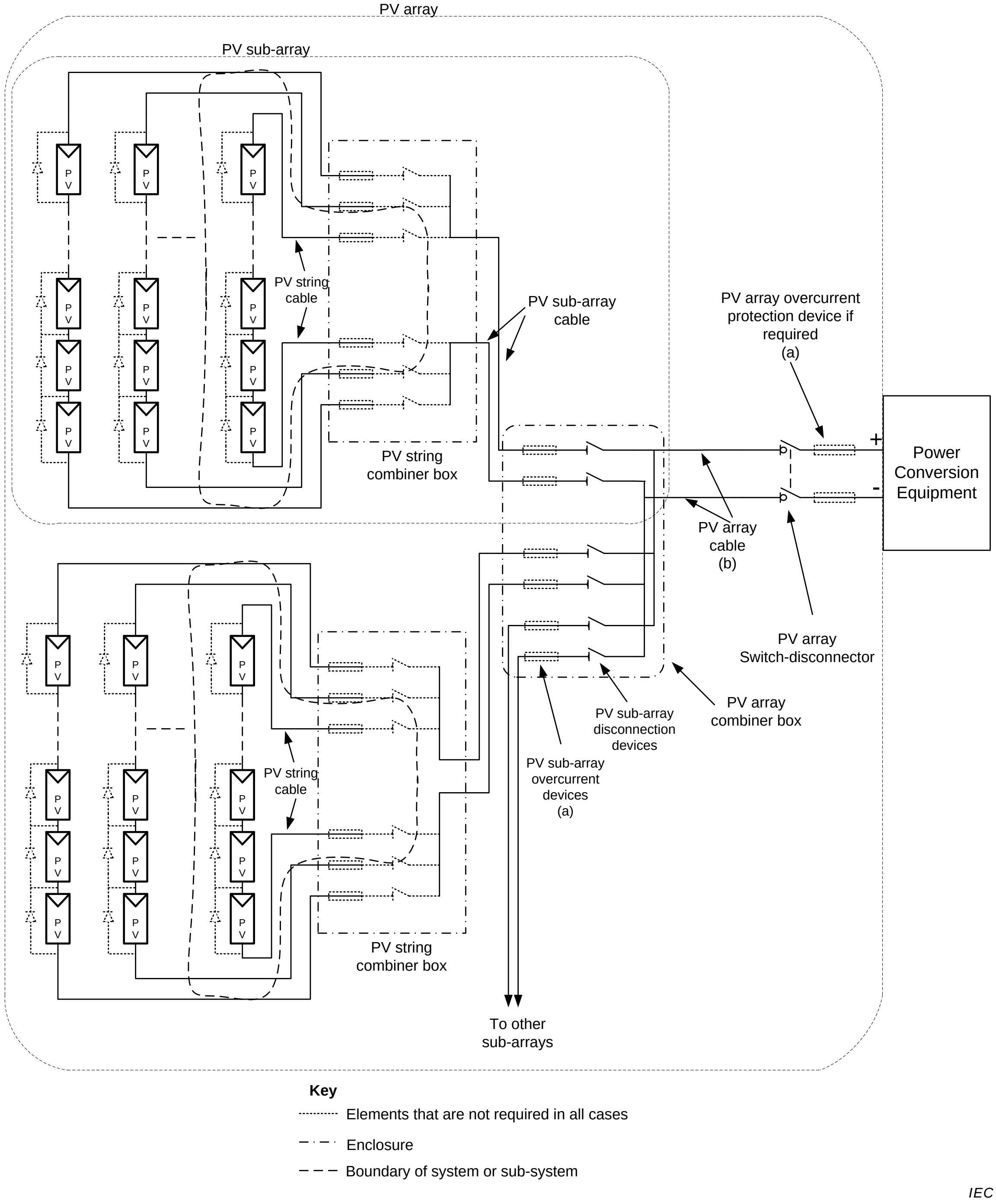
5.3 Array electrical diagrams

5.3.1 General

Figure 1 through Figure 4 show the typical array electrical configurations for PV power plants. Typical power plants employ multiple array-PCE “blocks” resembling the configurations shown in Figure 1 through Figure 3. Power plants may also employ string inverter configurations as shown in Figure 4, or module level micro-inverters.

5.3.2 Multiple sub-array configurations

PV arrays in power plants are most often configured with multiple sub-arrays. The sub-arrays are connected to large central inverters having multiple d.c. inputs, as shown in Figure 2 and Figure 3, or to PCEs with a single d.c. input via a separate PV array combiner box (refer to Figure 1). Overcurrent protection and cable sizing within the various sections of the PV array(s) are dependent on the limiting of any back-fed currents from the PCE and from parallel connected arrays.

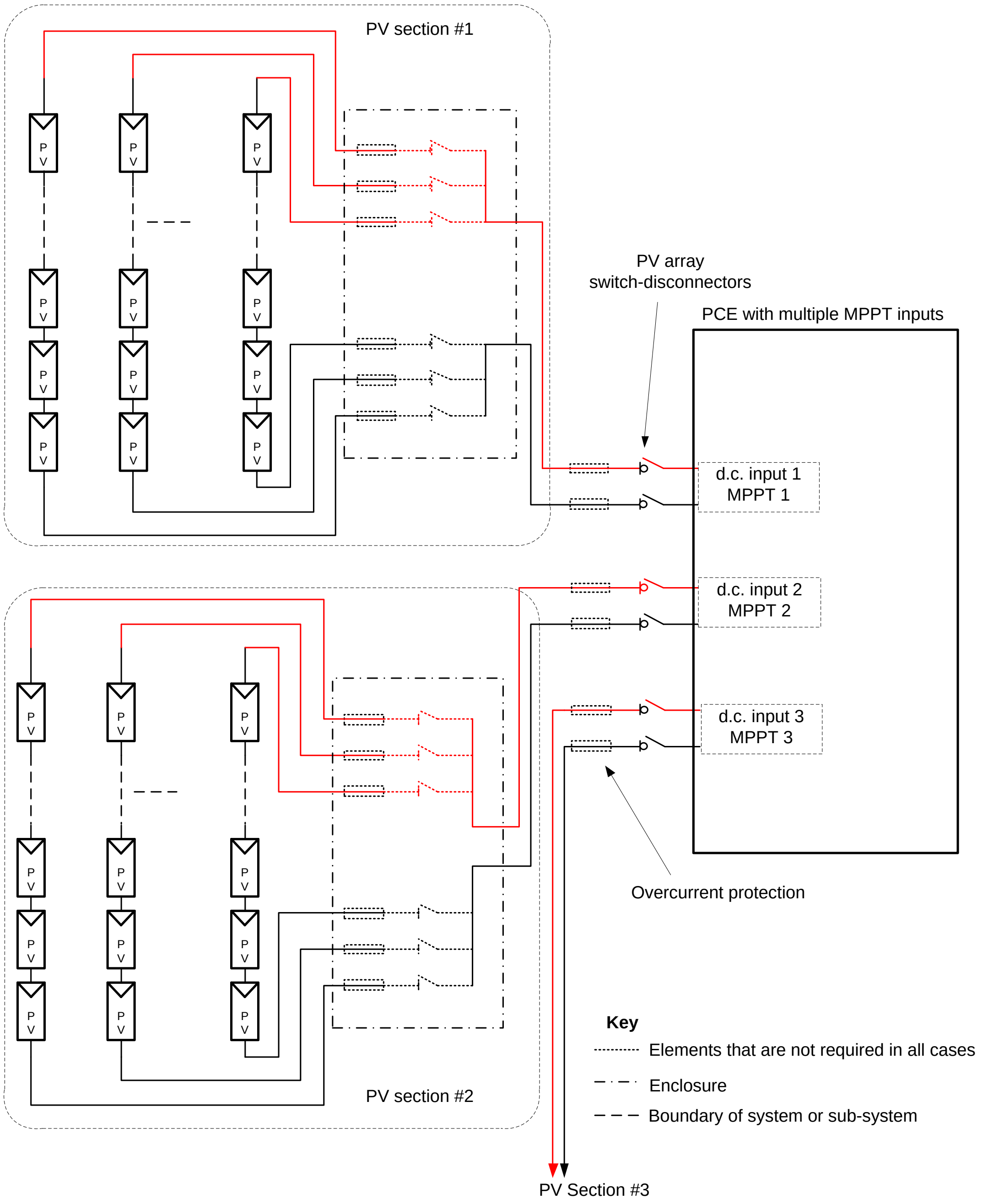


SOURCE: IEC 62548

a) Overcurrent protection devices where required see 6.3.

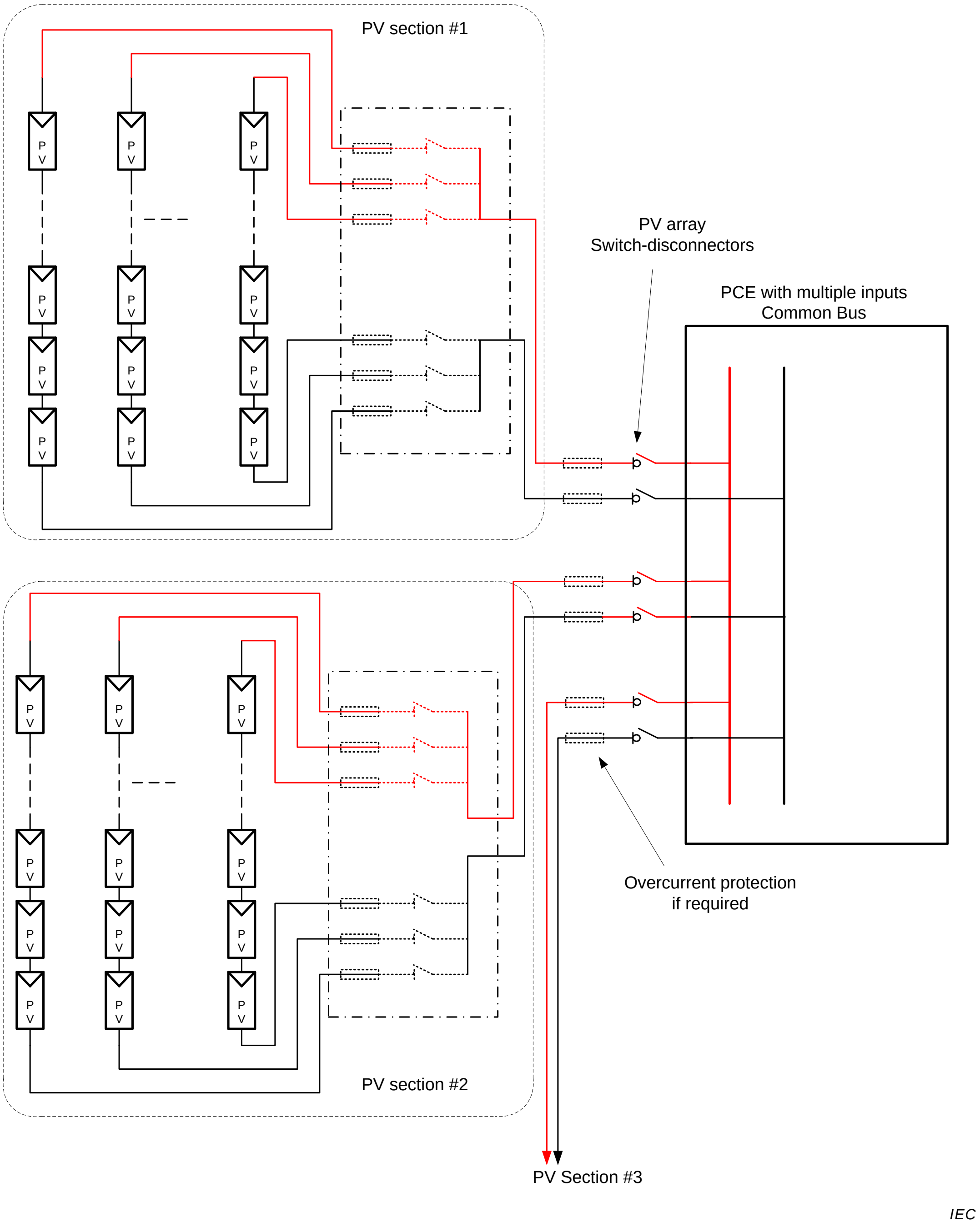
b) In some systems the PV array cable may not exist and all the PV strings or PV sub-arrays may be terminated in a combiner box immediately adjacent to or inside the power conversion equipment.

Figure 1 – PV array diagram – multiple parallel string case with array divided into sub-arrays



SOURCE: IEC 62548

Figure 2 – PV array example using a PCE with multiple MPPT d.c. inputs

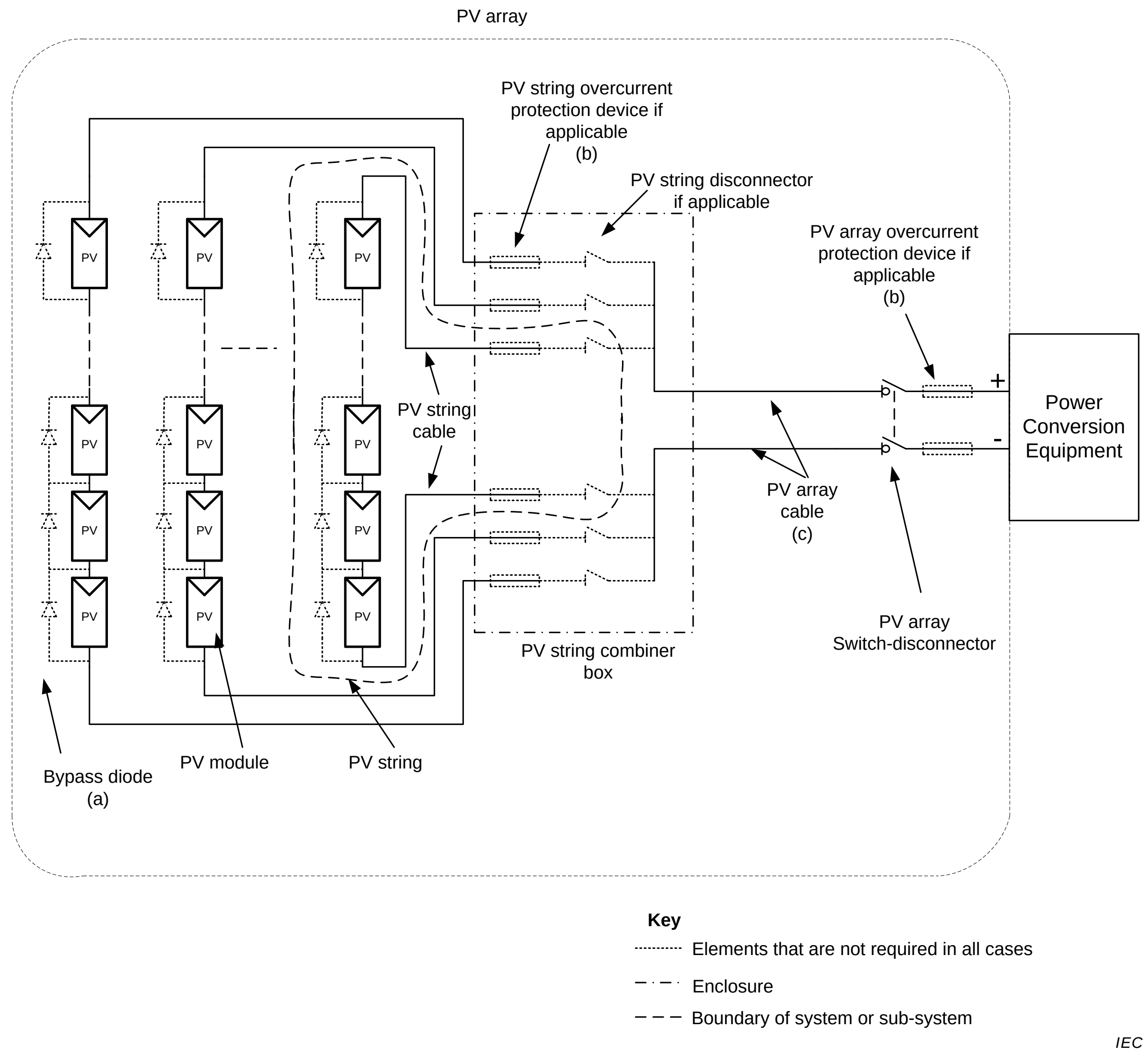


SOURCE: IEC 62548

Figure 3 – PV array using a PCE with multiple d.c. inputs internally connected to a common d.c. bus

5.3.3 Single array configuration

A single array PCE configuration is shown in Figure 4. This configuration generally applies for string or small central inverter applications (see also Annex A).



SOURCE: IEC 62548

a) If required bypass diodes are generally incorporated as standard elements of the PV modules by manufacturers.

b) Overcurrent protection devices where required see 6.3.

c) In some systems the PV array cable may not exist and all the PV strings or PV sub-arrays may be terminated in a combiner box immediately adjacent to or inside the power conversion equipment.

Figure 4 – PV array diagram – multiple parallel string example

5.3.4 Combiner boxes and string wiring harnesses

Figure 1 through Figure 4 depict typical configurations that include string combiner boxes. String wire combining functions may also be achieved with string wiring harnesses, which utilize connectors to aggregate multiple strings along a main conductor. The purpose is to reduce balance of system components and cost for systems with large numbers of parallel (especially low-current) strings. The harness main conductors are combined in a sub-array combiner box with larger fuses (e.g. 20 A to 30 A).

5.3.5 Series-parallel configuration

Deviations to the IEC 62548 requirement for uniform module string lengths are permitted under engineering supervision if string voltage control devices are employed, such as module or sub-string d.c. optimizers or converters. Any alternate string configuration shall conform to the limitations and requirements defined by the device manufacturers as part of their product installation instructions.

5.4 Energy storage in PV power plants

Energy storage systems incorporating batteries or other storage technologies may be used in PV power plants to address control or supplemental power requirements by customers, utilities or network operators. The requirements for energy storage battery systems are not addressed in this document. These systems tend to be coupled to the PV generators on the a.c. side, i.e. on the medium or high-voltage network, and therefore do not directly impact the d.c. array designs. For more information, refer to IEC 61427-2 and future IEC 60364-5-57.

5.5 Array physical configurations

5.5.1 Fixed tilt arrays

Fixed tilt arrays use structures that orient PV modules at an azimuth and tilt angle that is fixed year-round (see example in Figure 5). Arrays are fixed typically at the site latitude angle +/- up to 20° to optimize annual generation, but may be tilted at other angles to achieve specific performance and cost objectives. For example, lower tilt angles in the 5° to 20° range are sometimes used to reduce wind loading and mounting structure cost, to allow a higher power density of the plant, or to increase summer energy production if there are tariff incentives to do so. Lower tilt angles may result in higher soiling losses depending on site conditions and therefore should be a consideration. Time of day (TOD) incentives may also warrant orienting the arrays at an azimuth angle other than due south (or north in the southern hemisphere). Designs should consider the impact of module shading using suitable engineering analysis.

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Figure 5 – Example power plant with fixed tilt array

5.5.2 Adjustable tilt arrays

Adjustable tilt arrays are essentially fixed tilt arrays that can be manually adjusted once or more per year. The most typical adjustable tilt array uses a higher angle tilt setting for winter months and a lower angle tilt setting for summer months. The use of adjustable tilt arrays has historically been uncommon in PV power plants, but more recently there has been an increase in their use in markets and regions with low labour costs.

5.5.3 Single axis tracking arrays

Single axis tracking arrays employ structures that rotate PV modules along a single axis to follow the sun’s path. Most common for power plants is the horizontal N-S axis tracker, which rotates the modules from east to west throughout the course of a day along an axis that is horizontal relative to the ground plane. Single axis trackers may also be tilted (toward the equator) for greater energy capture.

5.5.4 Two-axis tracking arrays

Two-axis tracking arrays employ structures that rotate PV modules along both the N-S and E-W axes, thereby aligning the array to the direct beam angle of the sun throughout the day.

5.5.5 Concentrating PV arrays

Concentrating PV arrays are those that incorporate PV modules or cells that utilize lenses or other focal apparatus to concentrate greater sunlight on the cells. Concentrating arrays almost universally use either a 1-axis or 2-axis tracking mechanism. For the purposes of this document, all requirements pertaining to non-concentrating flat-plate arrays shall apply to concentrating PV arrays. Manufacturer instructions shall be followed to address any differences in calculation of system voltages, currents, and installation methods.

5.5.6 Central inverter configurations

Plants designed with large centralized PCEs or inverters are common, particularly with multi-megawatt sized systems. A typical centralized inverter design approach includes one or more inverters totalling e.g. 500 kW to 4 MW installed together at an inverter station (in a housing container or on an equipment pad) that includes a medium voltage transformer. Most inverters have an output a.c. voltage in the range of 200 V to 1 000 V. The transformer steps the low a.c. voltage up to a standard medium voltage or high voltage level, such as 20 kV. Figure 6 shows an example 1 MW centralized inverter layout using a N-S single axis tracker. The inverters are centralized within the array (see centre of figure) to minimize the total lengths of d.c. cable. The figure shows the cables emanating from the inverter station to PV string (or harness) combiner boxes distributed throughout the PV arrays. The MV or HV output cables exiting from the transformer are routed underground to a substation shown north of the array.

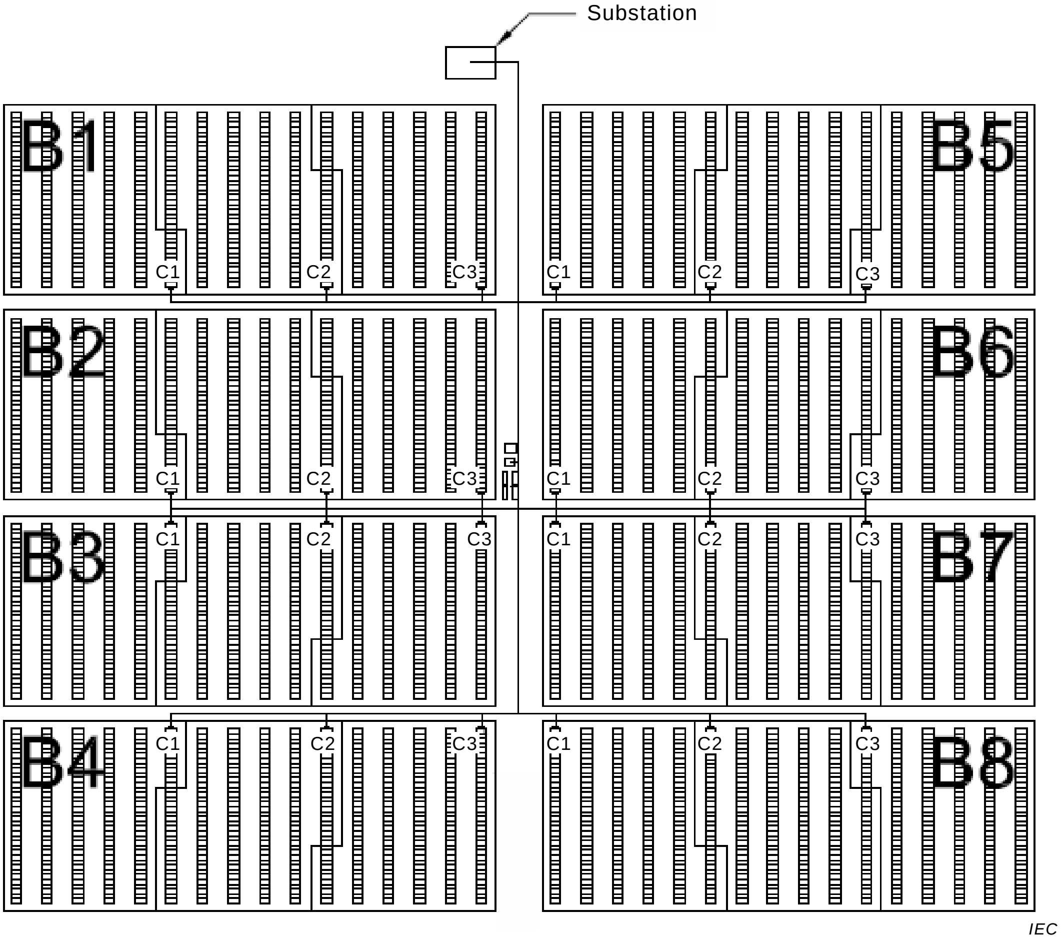

Figure 6 – Example layout of power plant central inverter based array

Smaller inverters may be used, resulting in more a.c. power distribution and less d.c. distribution. An efficiency and cost trade-off is used to evaluate these different options. As one example, there may be an advantage using 3-phase a.c. for cable sizing at a given voltage, but on the other hand the d.c. voltages are typically higher than the inverter outputs. Therefore d.c. cable cross-sections could be smaller and require only two conductors, compared to three or four (with neutral) conductors required for a.c.

5.5.7 String or module inverter configurations

Power plants may also utilize string or module level inverters. Figure 7 illustrates one approach with a similar N-S axis tracking array system. String inverters are mounted in every third row of modules. Typical string inverter configurations range from 300 V to 1 500 V maximum d.c. voltage, and single phase or three phase outputs in the 240 V a.c. to 480 V a.c. range. The output circuits are combined in protected harnesses, panels, or fused disconnectors and then connected to the LV side of a MV/HV transformer, as indicated in Figure 7.

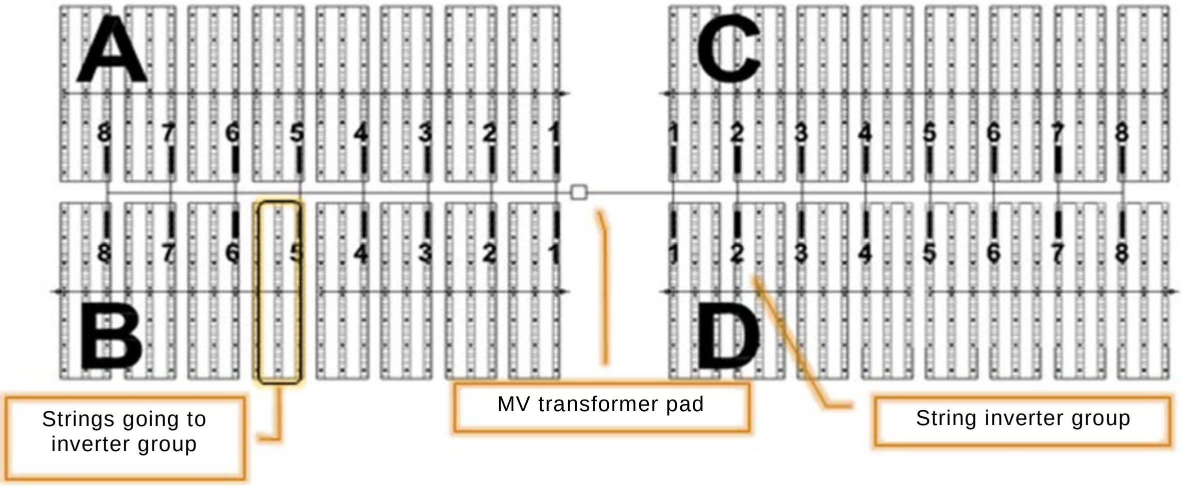

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Figure 7 – Example layout of power plant with string inverters

5.6 Mechanical design

5.6.1 Mechanical loads on PV structures

Power plant PV array support structures may be designed according to measured and documented site-specific conditions in lieu of loading requirements for PV modules defined in IEC 61215-2, and if approved by local approving authorities. Other deviations may be permitted under engineering supervision and approval by the applicable manufacturers and local approving authorities.

5.6.2 Wind

Local codes governing wind-load calculations for buildings may be either not suitable or not adequate for PV arrays. PV array structures may be designed and rated to measured site specific conditions and application-specific structural engineering calculations in lieu of local codes, where documented and approved by local approving authorities.

5.6.3 Snow

Attention should be given to snow loads on PV arrays in applicable areas. Care should be taken to address the effects of snow sliding on modules and resulting lateral loads imposed on modules or equipment on the lower edges of the arrays.

Embedment depth of below ground components shall be chosen considering the frost heave depth of the local site. Frost heave can also impact components with transitions between above- and below-ground.

5.6.4 Thermal expansion

Particular attention should be given to mounting rack length, module frame separation, cable management and rigid mechanical connections of long linear spans to account for thermal expansion and contraction. This may include the provision of expansion gaps for structures, or expansion fittings for conduits and cable trays.

5.6.5 Flooding

Where project sites are at risk of flooding, the height above the ground of modules, combiner boxes, tracker motors, and other electrical components should be considered. The type and construction of the mounting structures should also take into account the impacts of flooding and submersion, and site drainage.

5.6.6 Seismic activity

Where project sites are at risk of seismic activity, seismic loads on structures should meet requirements of the International Building Code or locally adopted codes. Where applicable, equipment standards with seismic qualification testing should be applied, such as:

- IEC TS 62271-210, addressing high-voltage switchgear
- IEC TR 62271-300, addressing high-voltage a.c. breakers
- IEC 60255-21-3, addressing measuring relays and protection equipment

Typical seismic considerations for PV plant include pier loading variations based on soil classification, lateral loads on fixed or tracking array structures, strengthened concrete equipment pads, greater requirements for bolting of enclosures to pads, use of flexible conduit (particularly for transformers), and retainer screws for tracking support structures.

IEEE 693 is also commonly referenced for complete substation design considerations.

5.6.7 Corrosion

Components in PV power plants are susceptible to corrosion from salt content in water, corrosive chemicals in the local atmosphere such as ammonia in agricultural areas, and numerous chemicals such as sulfates found in soils. It is important that local corrosive sources be considered and that components be appropriately protected. This applies not only to PV modules, structures (both sub-surface and above ground), cabling, and enclosures, but also to field-deployed inverters and their housings. Protection of sensitive internal components from extreme humidity may be better protected with air-tight enclosures or space heaters.

Corrosion design of steel piles may be based on an analysis of local site conditions, including a geotechnical evaluation of resistivity, pH, and levels of chemicals such as sulfates and chlorates. When cathodic protection systems are utilized, particular attention should be paid to the location of the cathodic protection system vents, as the emanating gasses can cause corrosion of nearby components.

Polymeric materials such as used in plastic wire ties are also subject to the effects of corrosion and shall be chosen appropriately per the site and application conditions.

5.6.8 Access

Rows of modules, particularly in very large fixed tilt systems, can be very long (e.g. greater than 500 m) with little spacing in between. With low-mounted structures, safe access from row to row may only be possible by traveling to the end of a row and around to the adjacent corridor. Narrow row to row spacing may prevent safe access with a motorized vehicle thereby limiting internal array access to personnel, who shall hand carry required tools and materials. These factors can be overlooked when there is a design objective to create a high-density array due to site limitations, but should not be ignored. Where pads or housings contain large equipment such as central inverters and or medium voltage transformers, roads shall be maintained for appropriate vehicle access (trucks or cranes) and turn-around capability. This also applies to emergency vehicles and local fire codes, which may dictate the maximum length of contiguous arrays and the minimum width of vehicle corridors in each direction.

6 Safety issues

6.1 General

PV arrays in power plants shall have no restrictions on maximum voltage ratings other than those imposed by the ratings of the equipment employed.

6.2 Restricted access

6.2.1 General

The entire PV array, inverter stations, medium or high voltage transformers, medium or high voltage collection switchgear and associated facilities in a PV power plant shall have access restricted to electrically skilled or instructed persons. Site specific safety rules and procedures should be established to limit access and ensure the safety of unskilled personnel. Examples include:

– Electrically instructed or ordinary persons trained to perform specific tasks (such as array cleaning or vegetation management) shall be permitted access under the supervision of the electrically skilled operators.

– Ordinary persons may be permitted in viewing areas, maintenance and monitoring facilities and other controlled areas of the plant.

6.2.2 Access to components

Power plant facilities that are secured to limit access to only electrically skilled or instructed persons may have protection approaches that differ from systems installed in publicly accessible sites. These persons shall be aware of PV circuits and components that may become or remain energized under various switching conditions, and understand the proper steps for working on or handling equipment. An adequate and well-documented protective device coordination scheme is recommended to reduce the risk of safety hazards.

6.3 Protection against overcurrent

6.3.1 DC overcurrent protection devices

Overcurrent protection devices used in the PV string, sub-array and array circuits other than those allowed by IEC 62548 may be permitted in PV power plants if selected as part of a protective device coordination study specifically suited to the plant.

6.3.2 Requirement for string overcurrent protection

String cables are routed along module frames, in metallic or non-metallic raceways, around edges of racking or tracking structures, and underground. They may also be contained in the same raceway as PV sub-array cables. Therefore, they are subject to earth faults, line to line faults (of string cables) and possibly line to line faults with other PV sub-array cables.

According to IEC 62548, string overcurrent protection in a combiner box or string harness system is required if:

$$((S_{\mathrm{A}} - 1) \times I_{\mathrm{SC\_MAX}}) > I_{\mathrm{MOD\_MAX\_OCPR}}$$

where S_{A} is the total number of parallel-connected PV strings in the PV array.

Some exceptions may be considered based on engineering analysis for power plants meeting requirements of limited access to ordinary persons. The following subclauses define additional engineering considerations in such cases.

6.3.3 String overcurrent protection sizing

The calculations in this clause omit the 2,4 x I_{SC} upper bound multiplier requirement for fuse ratings in IEC 62548. This allows greater design flexibility for PV power plants with larger numbers of parallel connected PV strings and potential fault currents.

Where string overcurrent protection is implemented, either:

a) the nominal overcurrent protection rating of the string overcurrent protection device shall be I_{n} where:

$$I_{\mathrm{n}} > 1{,}5 \times I_{\mathrm{SC\_MOD}} \text{ and}$$

$$I_{\mathrm{n}} \leq I_{\mathrm{MOD\_MAX\_OCPR}}$$

or

b) strings may be grouped in parallel under the protection of one overcurrent device such that:

$$I_{\mathrm{n}} > 1{,}5 \times S_{\mathrm{G}} \times I_{\mathrm{SC\_MOD}} \text{ and}$$

$$I_{\mathrm{n}} < I_{\mathrm{MOD\_MAX\_OCPR}} - ((S_{\mathrm{G}} - 1) \times I_{\mathrm{SC\_MOD}})$$

where

S_{G} is the number of strings in a group under the protection of the one overcurrent device;

I_{n} is the nominal overcurrent protection rating of the group overcurrent protection device.

NOTE In some PV module technologies $I_{\mathrm{SC\ MOD}}$ is higher than the nominal rated value during the first weeks or months of operation.

Engineering analysis may be used to evaluate whether these limits may be exceeded. For example, according to IEC 62548, strings can generally only be grouped under one overcurrent protection device if the module's maximum overcurrent protection device rating is greater than one less the number of strings protected times the module I_{sc} rating at STC conditions. The limitation is partly a reflection of the limited fault current available from neighbouring strings. In plant applications where there may be dozens or even hundreds of strings connected in parallel to the same central inverter, there are far fewer fault/environmental scenarios that result in low level fault currents, and it is reasonable to consider additional strings protected by a single device. This exception should only be applied under the following conditions:

- A failure mode analysis is performed to identify the scenarios of increased current back-feed and the resulting maximum current magnitudes and durations that may be imposed on the PV modules. This analysis shall also consider the current from parallel connected strings sharing the same overcurrent protection device.
- The modules are tested for their ability to withstand the identified current magnitudes and durations without thermal failure, or where the module failure mode does not cause undue risk to the plant.
- The module manufacturer approves the design configuration; otherwise product warranties may be voided.

6.3.4 PV sub-array and array overcurrent protection

Sub-array or array overcurrent protection shall be provided for their respective cables or string harnesses if more than two sub-arrays (or arrays) are connected to a single PCE or PCE busbar. Overcurrent protection should be sized according to the requirements of IEC 62548, with the following exceptions:

- The overcurrent device protection rating may be 1,25 x $I_{\mathrm{SC\text{-}ARRAY}}$ or less if there is inherent limiting of d.c. current. For example, if the array to inverter d.c./a.c. loading ratio is sufficiently high, the inverter will limit the current from the sub-arrays. This warrants a lower overcurrent protection device rating to protect the PCE from the maximum short-circuit current from the array, and/or to enable better reverse current fault protection without creating a risk of nuisance trips.

- The overcurrent device protection rating may be 1,25 x $I_{\text{SC-ARRAY}}$ or less if coordinated protection is provided with different trip values for forward and reverse currents.

In all cases:

- The array d.c. overcurrent protection measures shall be coordinated to ensure that fault current does not exceed the maximum short circuit input current rating of the inverter.
- The d.c. cable shall remain sized for at least the fault current available from its connected source, lest additional overcurrent protection be required on the source end of the cable.

6.4 Protection against the effects of insulation faults

The protective measures required by IEC 62548 for d.c. insulation faults apply to PV power plants. PV power plants with large connected parallel arrays are more likely to have lower measured insulation resistance values than smaller residential or commercial systems, due to aggregated module leakage currents and the current carrying capacity of large areas of earth, particularly during wet conditions. These resistance values can also be impacted by inverter-transformer topologies. Higher leakage currents increase the shock hazard risk to personnel, therefore insulation trip threshold values (corresponding to Table 2 of IEC 62548:2016) should be maximized to the extent possible without creating nuisance trip issues.

If needed, insulation resistance thresholds may be determined on a site specific basis, and treated similarly to coordination studies in a.c. electrical systems. Module leakage current tests can be used to engineer the appropriate maximum size of arrays connected to a single inverter d.c. busbar. For plants where measured insulation resistances vary widely over the course of a day or in rainy conditions, it is recommended that two thresholds be implemented: one for warning, and one for tripping. A warning threshold (set above a trip threshold) allows the plant to continue operating but may signal warnings to plant personnel or maintenance crews to limit certain activities within the arrays.

It may be necessary to reduce insulation resistance thresholds over time to address aging component leakage, but the corresponding increased risk of electrical shock shall be considered.

6.5 Protection against effects of lightning and overvoltage

6.5.1 Lightning protection

It is common for PV plants to take modest measures to protect equipment from lightning strikes. The extent of protection needed depends highly on the level of lightning activity at the project site. The lightning risk should be assessed during the detailed design phase using IEC 62305-2. In cases where lightning activity is very high, measures including the installation of air terminals bordering or throughout the array field may be warranted. However, for more typical installations, reasonable measures include:

a) Equipotential bonding of array racking or tracker structures.

b) Lightning/surge protection devices installed in the string or harness combiner boxes.

c) Lightning/surge protection devices installed on d.c. and a.c. side of inverters.

d) MV surge protection at substations and feeder termination points.

e) Building mounted air terminal and down conductors with ground rings for walk-in enclosures, operations and maintenance (O&M) buildings, or other facilities.

f) Lightning/surge protection devices for array communication equipment and cabling, other than fibre optic cabling.

All of these measures are recommended as a matter of best practice, and further study is recommended during the detailed design phase of the project. Items 2 and 3 are commonly supplied as options with commercially available combiner boxes and inverters, and item 4 refers to standard available MV surge protection devices.

Equipotential bonding of the array field components (Item 1) is recommended to achieve an effective 20 m by 20 m mesh (for example). An example is shown in Figure 8 below.

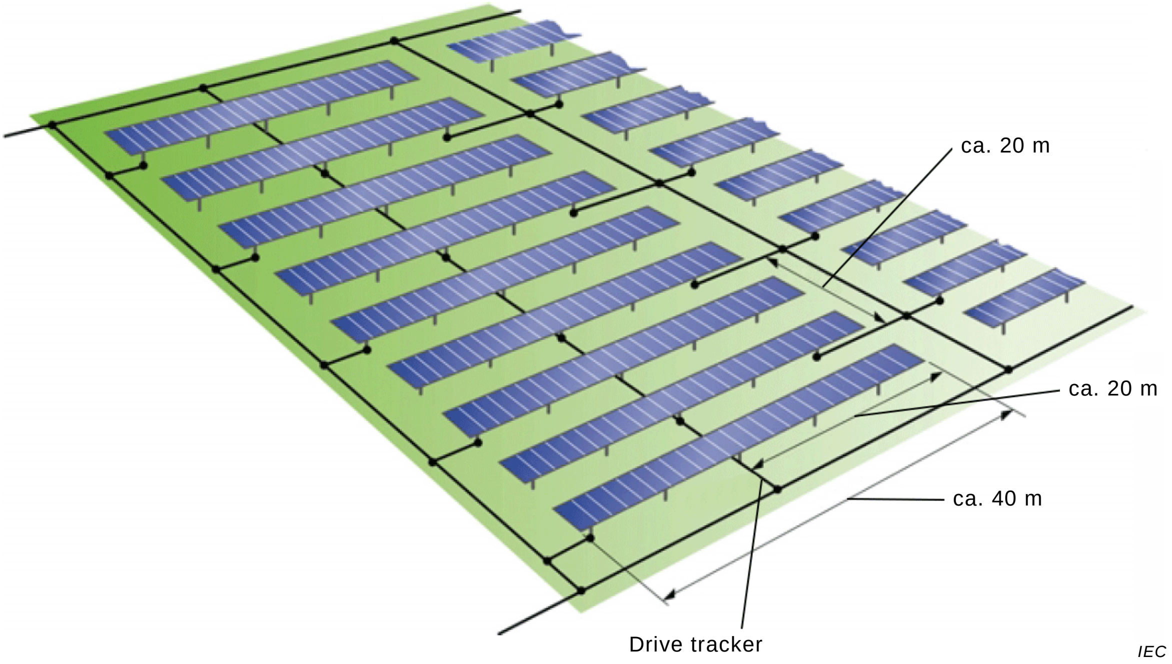

Figure 8 – Example ground plan for equipotential bonding of a PV array field

Buried ground cables on either side of the arrays make contact with individual (or alternating) rows to achieve the 20 m by 20 m mesh of component connections to earth. A 20 m x 20 m is only a recommendation. A soil resistance study throughout the plant area will give the correct information to determine the mesh width.

Metallic components of racking or tracker structures should also have inter-component continuity to ensure paths from the components to the nearest earth connection. Metallic enclosures of combiner boxes and the internal earthing connector of overvoltage protection devices should also be bonded to the racks or the underground cables, which continue in the trenches to bond to ground rings and terminals at the inverter pads. With respect to material and type, insulation, identification, installation and connections, protective bonding conductors shall comply with the applicable provisions specified IEC 60364-5-54.

This type of configuration reduces the damage potential to modules and combiner boxes for near strikes, which have greater probability than direct strikes. This approach will not be able to protect localized areas in the event of a direct strike but the higher degree of protection is usually only merited in locations with very high lightning activity.

Lightning and overvoltage surge protection is recommended in PV string or harness combiner boxes to help protect d.c. circuits and modules in the plant arrays. Lightning protection devices should be appropriately rated for the full open circuit voltage of the array, and should protect both poles.

Voltage rise is limited by having low cable resistance and inductance, so the effectiveness of lightning protection devices is dependent on the electrical distance between the device and the modules. Lightning protection in string or harness combiner boxes with higher numbers of strings and longer distances from outlying modules will therefore be less effective than those with fewer strings and shorter distances. Increased protection can also be achieved by including additional SPDs along the string cabling, adding resistance to the structure, or bonding conductors in the ground along the substructure rows (along the series path of modules). This will reduce the potential for higher coupled over-voltages in the strings and modules.

6.5.2 Protection against overvoltage

SPDs are recommended in combiner boxes and PCEs for over-voltage protection. The d.c. side SPDs shall be compliant with EN 50539-11 and be explicitly rated for use on the d.c. side of a PV system. SPDs should also be used to protect the input and output circuits of tracker controllers, as applicable. If the PV system is connected to other incoming networks (such as telecommunication and signalling services) SPDs shall also be required to protect information technology equipment. Selection and application of SPDs should in general follow the principles outlined in IEC 61643-32.

6.6 Protection against fire

6.6.1 Earth-fault protection

Fire protection is a high priority design consideration for any PV system, including power plants. In the context of earthing systems, fire protection is limiting fault currents to levels low enough to prevent localized heating and burning which can result in fire. Unearthed systems using larger string based inverters, for example, may use 300 mA trip current limits, which is higher than the touch safe limits but still effective for equipment and fire protection. The requirements described in 6.4 and corresponding clauses of IEC 62548, as well as in IEC 62109, address the relevant practical measures for earth-fault protection in PV power plants.

NOTE Earth fault protection schemes for PV arrays will be addressed further in future IEC 63112.

6.6.2 Protection against arcing currents

Arcing currents are a dominant cause of fire in PV systems. Arcing faults are best prevented by quality installation practices, properly torqued terminations, well installed and seated PV connectors, quality wire management (mechanical protection), and management of vegetation and rodent infestation. Arc-fault detection and interruption devices are not required but can be an effective part of PV power plant and property protection.

NOTE Components for DC arc detection and interruption in PV systems will be addressed in future IEC 63027, DC arc detection and interruption in photovoltaic power systems.

7 Selection and erection of electrical equipment

7.1 General

All power conversion equipment shall be qualified to IEC 62109-1, IEC 62109-2, and any other relevant parts according to the equipment type. In locations where the applicable standard is not available or enforced, PCEs qualified to alternate national or international standards may be employed provided there is:

a) sufficient engineering documentation of applicability (minimally basic electrical and construction safety requirements) to similar electrical and electronic systems, and

b) approval of the interconnecting electrical utility.

7.2 PV array design voltage

7.2.1 PV array maximum voltage

Maximum PV string length is dictated by the maximum system voltage rating of the module, inverter and other d.c. components. The maximum PV string open circuit voltage is calculated from the module STC Voc rating corrected for lowest expected operating temperature, per IEC 62548. The lowest expected operating temperature shall be the mean of annual extreme low temperatures; use of the record low temperature shall not be required. If sufficient data is available the mean data can be limited to sunlight hours, using a very low threshold for irradiance, i.e. 10 W/m^2 or less. The maximum calculated PV string length is often the optimum PV string length from a cost-performance perspective because of reduced losses in the d.c. cables and the lower quantity of cable required on a per W unit basis.

Where a target PV string length results in a calculated maximum voltage marginally above the maximum system voltage rating given straight-line approximations, further engineering analysis may be considered to determine the actual risk of over voltage conditions. The analysis should include the following:

- An evaluation of module/cell voltages as a function of ambient temperature and irradiance as the sun rises.
- Site weather factors that may result in module temperatures lower than ambient temperature, such as regular morning frost in winter. Locations where this phenomenon is likely shall be addressed in the voltage evaluation described above.

Evaluations of this type may result in PV string length designs larger than the straight-line methods defined in IEC 62548, but may be warranted if the lower PV string length results in meaningful limitations or energy losses during normal operating conditions.

7.2.2 Considerations due to inverter MPPT voltage window

Whenever possible, PV string lengths should be designed to prevent array MPPT d.c. voltage at the terminals of the inverter from dropping below the inverter’s minimum MPPT voltage rating. This condition forces the inverter to operate the array at non-MPPT values and therefore reduces system efficiency. Minimum PV string voltage calculations incorporate the module’s STC Vmp value corrected for mean annual ambient high temperatures and the expected delta between ambient and cell temperatures. The calculation should incorporate the module’s Vmp temperature coefficient if available. If not available, it is preferable to use the maximum power temperature coefficient rather than the open circuit voltage temperature coefficient. The evaluation should also account for additional voltage drop between the PV string terminals and the inverter, which occurs as a result of voltage drop on the cables, module mismatch, and module voltage degradation over time.

7.2.3 Considerations due to inverter efficiency

Inverter efficiency varies as a function of d.c. voltage, and efficiency curves as a function of both power and d.c. voltage are normally provided by manufacturers. Efficiencies tend to be slightly lower at the high end of the inverter MPPT voltage window because of the increased switching losses across the power electronic devices as they turn on and off. As a result, the optimum PV string length may or may not be the maximum PV string length if the inverter voltage window is large enough to accommodate several alternatives. Where these alternatives exist, it is recommended to evaluate the efficiency trade off of using the highest possible PV string voltages to minimize power loss in the d.c. cables and using lower PV string voltages to maximize the inverter efficiencies.

7.3 Component requirements

7.3.1 General

The component requirements of IEC 62548 apply for PV power plants except where modified in this clause.

7.3.2 PV combiner boxes

7.3.2.1 Environmental ratings

The component environmental rating and design of PV combiner boxes should be guided by IEC 61439-1 and IEC 61439-2. Additional considerations specifically related to PV power plant applications should be considered. For example:

a) Typical PV installations have an expected life time of 25 or more years. Components used in the PV system should be selected to have an operational life time equal to the PV installation expected life time. Alternatively, anticipated replacement intervals should be defined for components with shorter life expectancy.

b) Components installed within a PV installation are typically exposed to environmental conditions that are amplified by the location or method by which they are installed.

c) Exposed components within a PV installation are subject to cyclical stresses associated with day to night temperature and irradiance variations, as well as variations from intermittent cloud cover. Component cyclic heating and cooling is exacerbated by the current and power cycling, which is coincident with the sunlight and temperature variations. This can impact component lifetimes in general, degrade enclosures and markings, increase expansion and contraction, and put stress on electrical connections. Properly selected and torqued connections and regular maintenance helps to limit the impact of these variations.

d) Environmental conditions specific to the area of the PV power plant. For example:

    1) Wind-blown sand, dirt and plant material. In susceptible areas, the impact on equipment is dependent on the frequency of wind storms, their intensity (wind speed), duration, and the size of the particulate (fine sand or course dirt). Prevailing wind directions may also be important to characterize. For example, module back sheets may be more vulnerable to wind-blown sand than the front side glass. Coordination of IP ratings of the enclosures and the equipment inside should also account for these unusual environmental conditions.

    2) The corrosive nature of the soil.

    3) The proximity to sources of humidity (salt water, fresh water).

    4) Susceptibility to flooding. As discussed in 5.6.5, enclosures should be installed at heights that consider projected flood levels.

e) Special attention should be given to the choice of materials (polymers and different metals in contact) and termination types to address the thermal cycling duty. Gasket material in particular should be rated for the environment of use and a replacement schedule identified if applicable.

f) Additional guidance for enclosures operating in high temperature conditions is provided in IEC TR 60890.

g) Enclosures that are installed adjacent to arrays or equipment pads sometimes use conduits or ducts to transition cable from the enclosure to direct-buried laying configurations. This can result in excessive moisture ingress from the ground into the enclosure. Steps may be taken to prevent this ingress by sealing the conduit or duct using a sufficiently watertight, insulated and fire-resistant material, such as a suitable sealing foam or putty. If such sealing needs to be applied to the enclosure as well, equipment manufacturer guidelines should be followed in order to ensure that any enclosure IP rating shall suit the environmental conditions. This IP rating should apply for the relevant orientation and mounting position of the enclosure.

7.3.2.2 Location of combiner boxes – Considerations due to performance, operation and maintenance

Mounting locations are preferable in the shade (e.g. behind or under modules) but shall provide appropriate working access for maintenance personnel. Locations and arrangements should result in clear and uncomplicated procedures for O&M personnel, and locations should be well documented in O&M documentation.

7.3.3 Disconnectors and switch-disconnectors

7.3.3.1 General

This clause focuses on d.c. disconnectors and switch-disconnectors, which have unique applications in PV systems. Disconnectors and switch disconnectors used in the d.c. circuits of PV power plants should comply with the requirements of Annex D of IEC 60947-3 AMD2(2015). The amendment specifies utilization categories modified for PV-specific applications, as follows:

- DC-PV0 – disconnection when no current is flowing
- DC-PV1 – connecting and disconnecting single PV strings where reverse currents and significant overcurrent cannot occur
- DC-PV2 – connecting and disconnecting PV circuits where significant overcurrents may prevail and where current flow can be in both directions.

Devices of utilization category DC-PV0 shall be marked “Do not operate under load” unless the device is interlocked to prevent such operation.

7.3.3.2 Disconnect environmental ratings

The environmental rating and design of PV array disconnects should be guided by IEC 61439-1 and IEC 61439-2. The additional considerations specifically related to PV applications identified in 7.3.2.1 apply to disconnect assemblies as well.

7.3.3.3 Locations of disconnects

7.3.3.3.1 General

Many factors should be considered when determining the location, type, and quantity of d.c. disconnectors, including safety, the array size (power and area), inverter d.c. input capabilities, sub-array sectionalizing objectives, and O&M.

7.3.3.3.2 Considerations for safety

The selection and coordination of disconnectors and switch-disconnectors for isolating functions should carefully consider the need for load-break capability at various locations. Disconnectors (without load-break capability) are highly useful for maintenance functions when there is a convenient method to shut down the circuit(s) to stop current flow, e.g. by shutting off the inverter.

Switch disconnectors are recommended minimally for sub-array circuits at combiner box locations, and for array or sub-array circuits at the inverter pad. This allows operations personnel to isolate a faulted sub-array from either location in emergency situations, without having to navigate a relatively large distance. Furthermore, limiting the load-break disconnector locations to the inverter pad reduces options should equipment on the pad become unsafe during a thermal failure.

7.3.3.3.3 Considerations for fire protection

Disconnectors located inside an inverter enclosure may not be accessible in the event of an inverter fire, therefore safe access to sub-array switch-disconnectors should be considered. These may be maintained at a safe distance on the same pad, or at combiner box locations, depending on the size of the system, the array and the pad.

7.3.3.3.4 Considerations for operation and maintenance

In large array fields the pattern and placement of disconnectors (and combiner boxes) in sub-arrays should be standardized to the extent possible for O&M personnel. When working in the arrays, visibility can be limited and sub-arrays are often not physically separated according to the sectionalized electrical circuits. Standardized equipment locations reduce the likelyhood that personnel will operate the wrong disconnector to work on a particular string or sub-array circuit.

Placement of disconnectors should account for the impacts of desired or recommended routine maintenance. Sub-array isolation that does not require inverter or larger array disconnection can minimize downtime and lost production of the plant, without discouraging preventative maintenance practices. Designs should also account for safe and efficient coordination of switching (such as lock-out tag-out procedures) when considering the location of disconnectors.

7.3.3.4 Markings and placards

To aid plant personnel (i.e. on-site operating and maintenance) and others (i.e. emergency service personnel), placards, maps and/or descriptions should be posted at inverter pads and other central locations that identify critical disconnection locations. For example, in a large power plant a placard (site map or description) highlighting the inverter pads or inverter group switches may be posted at the main power plant entrance or with security personnel. More detailed placards may also be posted at each inverter pad illustrating the location of inverter and sub-array switch-disconnectors. In very large plants it is also useful to number and label access roads and corridors, and to place placards with large characters that identify the inverter or inverter pad number.

In smaller PV power plants, a single placard identifying the location of switch-disconnectors at each inverter pad may be sufficient.

7.3.4 Cables

7.3.4.1 Current carrying capacity (CCC)

String conductors are allowed to be sized at 1,5 x I_{SC} of the indivdual string if array overcurrent protection is designed according to engineering analysis as described in 6.3.3.

In power plant configurations resulting in long runs of cable between the PV string terminals and PV string combiner boxes, further evaluation is recommended to determine if the cables should be increased in size for a reduced voltage drop. Voltage drop on PV string cables or harnesses rarely reach levels considered as limits in standard a.c. branch circuits for end-use loads. Cable sizing and voltage drop decisions are largely determined by a cost-performance trade-off analysis. Historically this had led to designs limiting average cable voltage drop to 1 % to 1,5 % at peak power conditions, but these are not requirements. The CCC of above and below-ground cables should incorporate de-rating factors associated with spacing and soil thermal resistivity calculations in accordance with IEC 60364-5-52. Designers should also refer to IEC 60364-5-52 for considerations of using parallel cables to ensure proper current sharing.

7.3.4.2 PV sub-array cable sizing

PV sub-array cable sizing should be guided by requirements in IEC 62548. Some variation and exceptions may be considered based on engineering analysis for power plants meeting requirements of limited access to ordinary persons. This clause defines additional engineering considerations in such cases.

7.3.4.3 Cable ratings for fault protection

Variations on overcurrent protection ratings identified in 6.3.4 may have an impact on cable current ratings.

Nevertheless the d.c. cable size shall remain sized for the larger of the overcurrent protection device rating, or the fault current available from its connected source, lest additional overcurrent protection be required on the source end of the cable.

7.3.4.4 Type

The requirements of IEC 62548 apply with the following exceptions:

Flexible cables (Class 5 or above according to IEC 60228) are required where terminated with connectors meeting IEC 62852. Cables routed on moving parts of tracker systems should follow the recommendations in 7.3.4.7. Class 5 cables are not required where cables and connectors are fixed in a manner such as described in 7.3.4.6.

PV sub-array cables compliant with regional and national standards, such as EN 50618 or UL 4703, are applicable if allowed by the approving authority and if appropriately selected for the routing method (trunk, duct, direct-buried underground, etc.) Halogenated (non-halogen free) cables are acceptable in ground mounted free field applications.

Aluminium cables are permitted for fixed installations of d.c. circuits and medium or high voltage a.c. circuits in PV power plants.

See IEC 62930.

7.3.4.5 Cable protection from physical damage

Choice of cable management means shall be appropriate for the design, application, local site conditions (thermal effects, flora, fauna, wind e.g.) and maintenance protocols. PV string cables and harnesses are most often routed above ground in air or exposed channels or trays. Often they are routed behind modules and therefore shaded from the sun, but portions between modules or racks may be in direct sunlight. The cables need not be in conduit or tray continuously and may be secured to racking systems. Cables should be protected from physical damage by avoiding pinch points, routing clear of potentially sharp edges of racking and structural metals, preventing excessive movement from wind, and protection from rodents if necessary. Segments of cable regularly exposed to sunlight should be monitored over the life of the system for degradation, despite being rated for UV exposure.

7.3.4.6 Cable securement

Cable securement methods shall have the objective of preventing damage due to excessive stress, tension, or sharp radii. Common methods of securing module to module leads and homerun strings or harnesses to the array structure include wire ties, clips, channels and lightweight trays or wire cages. Plastic or metallic wire ties are used, each with their own challenges. Plastic wire ties should be UV resistant and of sufficient strength and thickness to last several years. They are not generally expected to last the life of the plant and owners shall anticipate their periodic replacement as a preventative, not a corrective measure. Preventative replacements reduce the risk of excessive loading on connectors, which can lead to high resistance failures and arcing. Polymeric materials in plastic wire ties are also subject to the effects of corrosion and shall be chosen appropriately per the site and application conditions. Metallic wire ties may be used but due care shall be taken to prevent the edges from damaging the cable insulation over time and causing damage to cable and conductor due to high voltage discharge events between clip and conductor. This is true with coated metallic ties as well.

More extensive use of cable trays and channels reduces the reliance on wire ties for supporting cable weight. This may result in greater equipment costs but lower maintenance costs. String or harness cables run in shallow channels or trays need securement by cover, wire tie, clips or other means as well, as these cables move considerably from wind, current cycling, and thermal expansion.

Cables do not necessarily require securement if routed in deeper cable trays or wire cages, but it is recommended that wire ties or other similar means be used to contain bundles. The larger trays or cages result in higher material costs, but these costs may be lower than the labor costs associated with properly securing all of the cables to the support structure.

7.3.4.7 Cable routing and transitions on trackers

In tracking systems, cables run from moving equipment (module array) to stationary equipment such as piers, trays or conduit. Here PV conductors with Class 5 stranding in accordance with IEC 60228 are recommended for reliability of regular bending cable. Bend radii shall meet cable manufacturer requirements. Measures should also be taken to ensure that earth cables, braids, or jumpers used for bonding tracker parts, and their connections, are designed to maintain integrity given the movement and cycling expected during the life of the system.

While not a requirement, it is recommended to use flexible UV- and weather-resistant conduit, or metallic messenger cable, or equivalent for the section of moving bundled cables linking the moving and stationary equipment. This guides the cables away from moving parts. Conduit should meet UV, temperature and flexibility requirements for outdoor installations.

Where d.c. power and control cables with different insulation ratings are transitioned from a fixed installation to moving tracker components, steps shall be taken to maintain adequate separation between the differing cables. Requirements addressing proximity of wiring systems to electrical and non-electrical services in IEC 60364-5-52 shall apply.

7.3.4.8 Use of cable trays (trunks)

Cable trays or trunks are a common and useful method of cable routing in PV plant applications, due to the distributed contribution of circuits to string or central inverters. The following items should be addressed for their use. Figure 9 shows examples of above-ground, horizontally mounted trays.

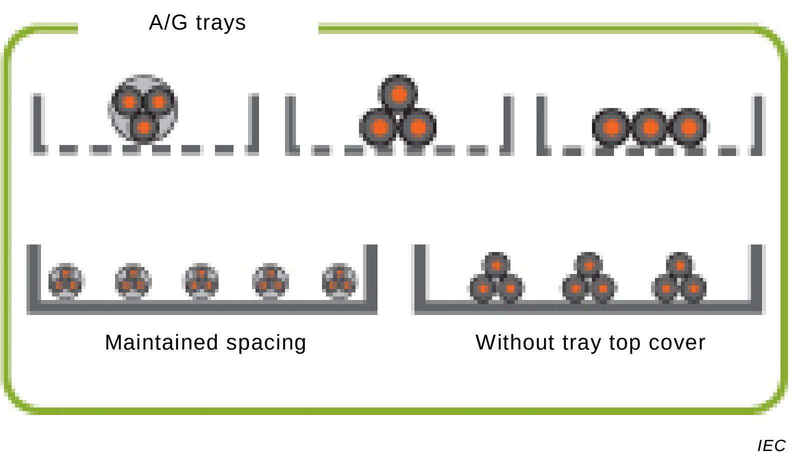

Figure 9 – Example of above-ground cable tray configurations for PV plants

The following are requirements and recommendations related to the use of trays:

- Cable sizing calculations shall account for quantity, spacing and placement, in accordance with IEC 60364-5-52.
- In power plant applications, many sections of tray do not contain a large number of cables, and therefore the loading per meter is low relative to those used in typical tray support design guidelines.
- Span distances between supports should be determined by manufacturer recommended calculations of loads and length.
- Perforated trays on sides and bottom are recommended to maintain lower cable ambient temperatures and reduce water build-up. Potential damage to cables from fauna and vegetation shall be considered when using perforated trays.
- Tray covers are recommended to reduce long term exposure to UV and to offer additional protection against rodents and other fauna. Careful evaluation of conditions may result in

the decision not to use covers however, if UV exposure is limited or less pressing than thermal issues.

7.3.4.9 Use of underground cable

7.3.4.9.1 General

Cables in trenches, whether in ducts or direct-buried, should be sized according to spacing and thermal resistivity of soil calculations according to IEC 60364-5-52. Site specific solar output load profiles may be used in place of 100 % load factor assumptions to determine effective loading criteria, using methods described in IEC 60853, all parts, or similar methods.

NOTE Currents in PV system cabling are predictably cyclic due to the daily cycles of solar irradiance, and cable ratings can therefore be determined using load factors that are less than 100 %. With cables in underground installations, there is a time lag between the temperature rise of the cable and temperature rise of the duct structure and/or surrounding earth. This heating time lag permits assigning higher current ratings for underground cables which do not carry a constant current over a 24 h period.

The following sublcauses provide example profiles and guidelines for multi-layer mixed use trenches that are used in PV power plants. These profiles are examples only and the details are not intended to be mandatory. IEC 60364-5-52 is the governing standard for fundamental depth and spacing requirements.

7.3.4.9.2 Use of ducts in trenches

The use of ducts for PV d.c. and medium voltage a.c. cables are recommended particularly for sections of cable that run underneath roads or areas where routine passage by maintenance vehicles is expected. Figure 10 shows an example trench profile diagram with ten pair of d.c. sub-array cables and a.c. control cables in ducts underneath a road.

Refer to local requirements, but some general recommended practices are as follows:

- Backfill bedding should be compacted to at least 90 % of original compression, and should be filtered of stones and rocks. When 90 % compaction is not feasible with multiple layers, trenches shall be backfilled in layers to the same level of compaction as existing grade and testing should be performed to verify the target compaction level is achieved. Such testing should be performed at determined intervals (for example 500 m) along the trench path.
- Sand bedding is not required if trench soil is free of stones.
- Warning tape should be placed at a depth of 300 mm below the surface to warn contractors of the presence of cables. Trenches greater than 1 m wide should have two or more equally spaced warning tapes.
- If trench depth is greater than 1,5 m, shoring of the walls should be provided.

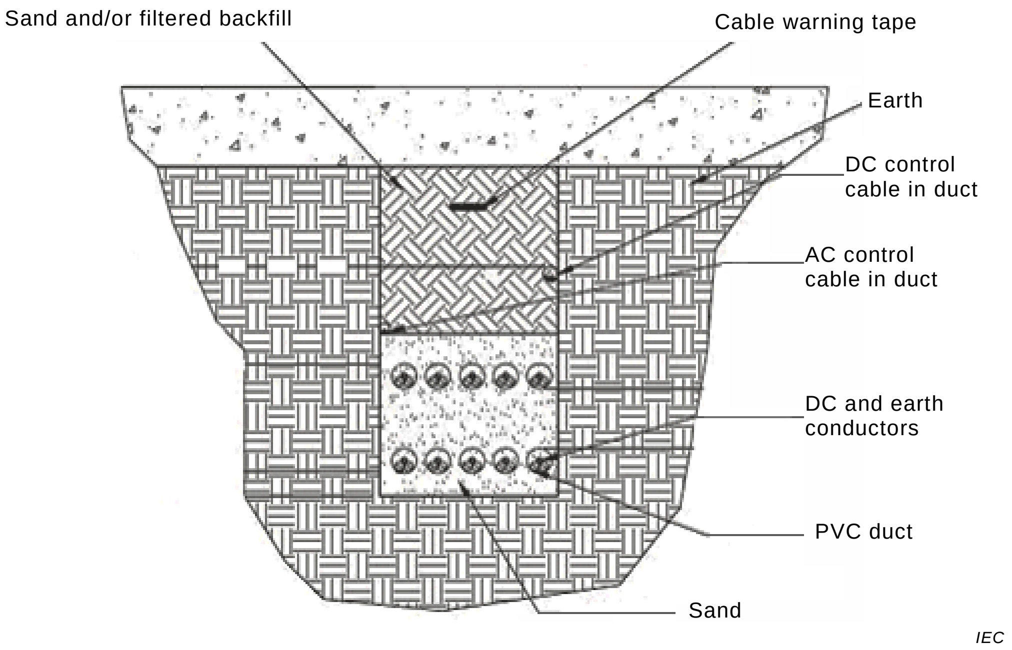

Figure 10 – Example trench diagram with cables in ducts

7.3.4.9.3 Use of direct burial cable

Figure 11 and Figure 12 show example profile diagrams of trenches carrying direct buried d.c. and a.c. cables, respectively. Each includes communication cables, with recommended separation and depths. These examples are not restrictive, and it is possible for example to include d.c. and MV or HV a.c. cables in the same trench with proper depth spacing.

Dimensions in millimetres

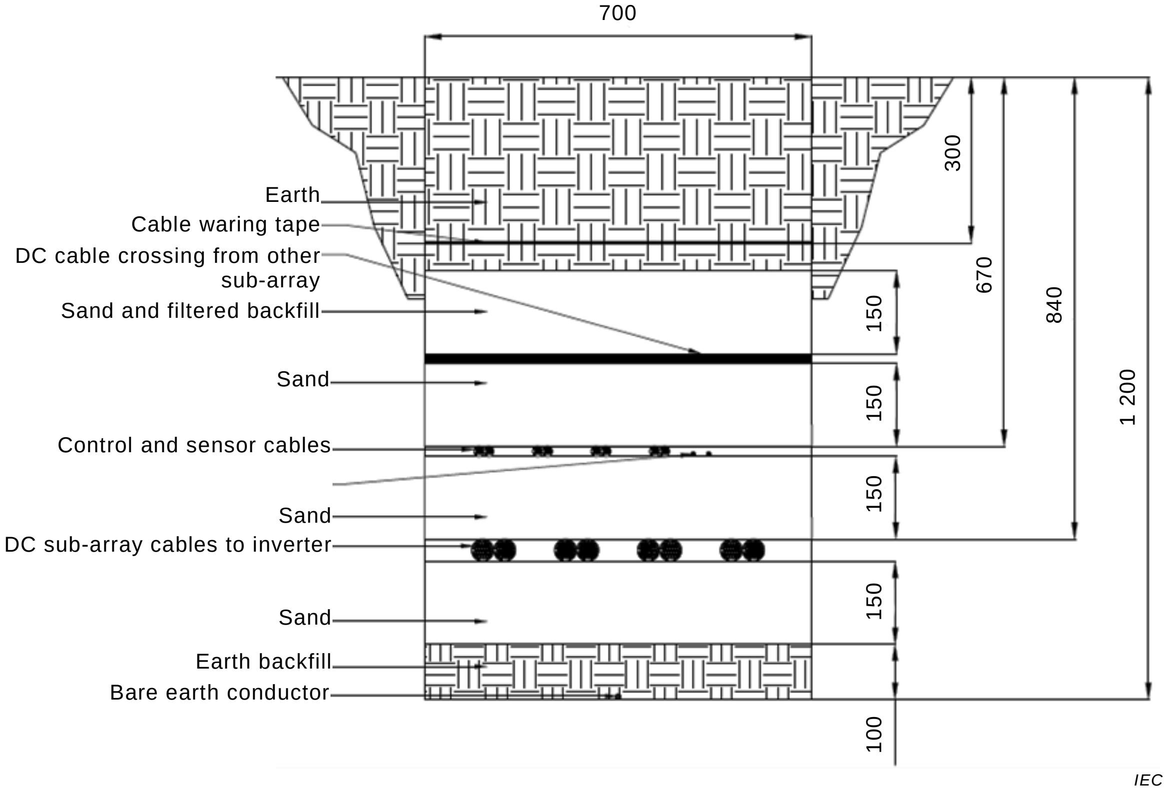

Figure 11 – Example trench diagram with direct buried d.c. and communication cables

Dimensions in millimetres

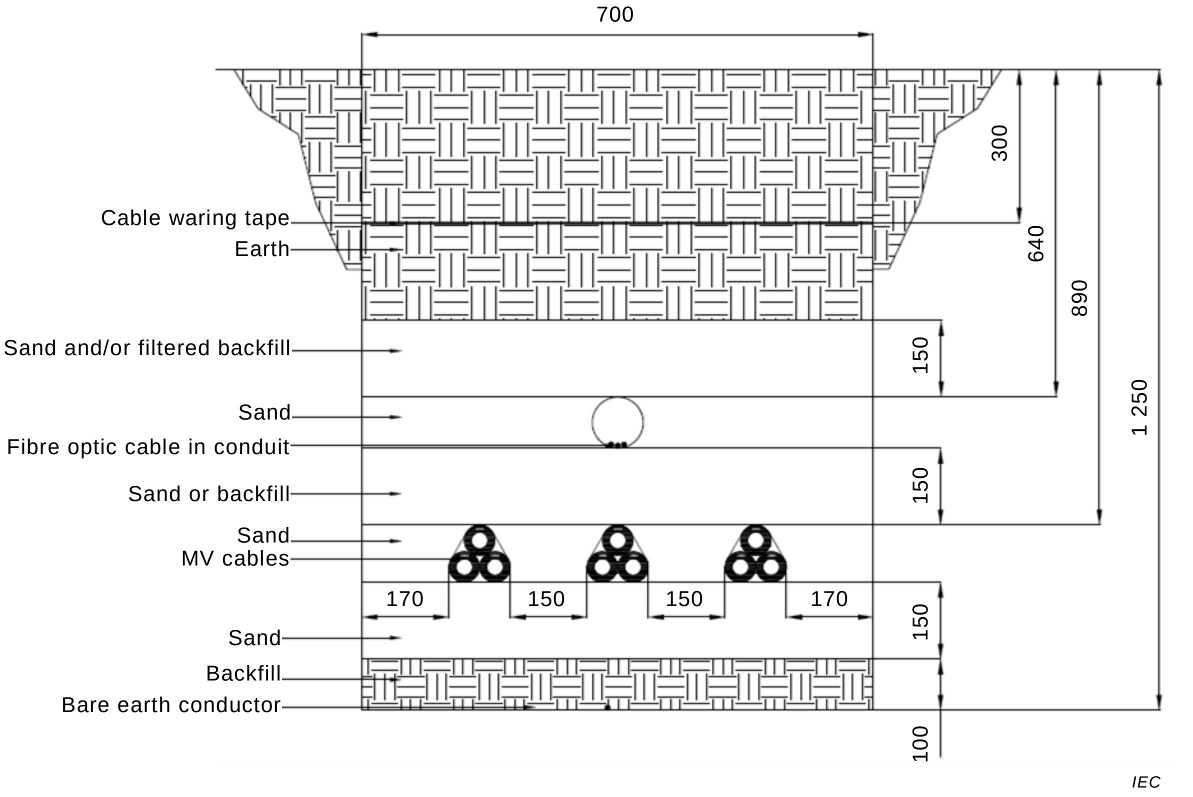

Figure 12 – Example trench diagram with direct buried medium voltage a.c. and communication cables

The general recommended practices identified in 7.3.4.9.1 should be followed, as well as the following:

- Cable route markers should be placed at 50 m spacing and/or at turn points.
- Cables should be at least 50 mm from the trench wall(s).

7.3.4.10 Use of aluminium cables

Aluminium cables offer a cost advantage over copper but have greater issues associated with expansion and contraction than copper cables in locations prone to thermal- and current-cycling, and therefore present a greater risk of terminal stress and weakening connections. This should be factored in to sizing and securement design particularly for long runs of cables in above ground trays or trunks.

Specific considerations should be addressed when using aluminium cables in order to reduce the risk of thermal failures:

- Oxide film build-up on the aluminium cable terminals shall be removed and a special treatment (paste) shall be used to inhibit the formation of a new oxide layer.
- Terminals designed for connecting aluminium cables shall be used.
- Cable lugs designed to connect aluminium cables to copper busbars shall be used.
- Terminals should be checked again after a period to avoid loosening contact pressure.
- Cables connecting to smaller combiner boxes or assemblies should have supplemental cable securement to reduce cycling tension on the connectors and assembly.
- Connectors for transitions to copper or other material shall be dual-rated as appropriate.

7.3.4.11 Insulation piercing connectors

Insulation piercing connectors (IPC) are permitted for wiring harness assemblies and other wiring connections. Strict adherence to connection and installation instructions is required to ensure durable connections and to minimize the risk of resistive thermal failures.

7.3.5 Trackers

Where used in PV power plants, solar tracker components, controllers and/or systems should be evaluated to IEC 62817. Tracker environmental ratings shall be suitable for the installation. Similarly, optional tests addressing environmental factors such as snow load or wind-blown dust should be included as applicable for the installation. Additional tests of tracker controller input and output circuits to IEC 61000-4-2 are recommended for electrostatic discharge immunity.

Tracker controller enclosures may be susceptible to water ingress and other environmental factors. The additional considerations specifically related to PV applications identified in 7.3.2.1 apply to tracker controller assemblies as well.

8 Acceptance

8.1 General

PV power plant acceptance criteria generally include the successful completion of inspections, commissioning tests, and performance validation tests. The recommendations in this clause apply primarily to the low voltage PV d.c. and a.c. sub-systems of the PV power plant. Tests and acceptance of medium voltage components and systems are highly specific to the particular equipment and the installation, and should be dictated by manufacturer recommendations, utility requirements, and local and national requirements.

8.2 Monitoring

Monitoring protocols for solar resource, weather, and PV system performance should comply with the requirements of IEC 61724-1. Large plants with multiple data logging stations benefit from using GPS based-time stamps to ensure that data is properly synchronized.

When using custom weather stations to support plant designs, it is recommended that wind speed measurements be capable of capturing 3 s averages to address wind gust design criteria.

8.3 Commissioning tests

Commissioning test and inspection protocols shall include, at a minimum, those included in the Category 1 test regime specified in IEC 62446-1. String I-V curve and thermal imaging tests defined in the Category 2 test regime of IEC 62446-1 should be considered for sample portions of the plant. In plants where string harnesses are used, sample IV curves may be taken at the harness level rather than the string level.

8.4 Preliminary performance acceptance test

It is recommended that preliminary performance acceptance test protocols include the requirements of IEC 61724-2. Additional steps such as verification of sample module flash test values according to the module rated power and tolerance can be considered.

8.5 Final performance acceptance test

It is recommended that final performance acceptance test protocols include the requirements of IEC 61724-3.

9 Maintenance

It is recommended that plant maintenance practices and procedures follow the applicable requirements of future IEC 62446-2.

10 Marking and documentation

10.1 General

The requirements and recommendations in this clause apply primarily to the low voltage PV d.c. and a.c. sub-systems of the PV power plant.

10.2 Labelling and identification

10.2.1 General

Component labelling and identification shall comply at a minimum with the requirements of IEC 62446-1.

10.2.2 Labelling of disconnection devices and combiner boxes

Disconnection devices and combiner boxes shall be marked with an identification name or number according to the PV array wiring diagram. If the disconnecting device is located in a combiner box, the switch may be identified by the combiner box name and numbering.

All switches shall have the ON and OFF positions clearly indicated and further safety information might be provided inside the enclosures.

10.3 Documentation

Documentation for a PV power plant is extensive and largely specific to project, contractual requirements, utility requirements, and other factors. Documentation of the PV power systems shall comply at a minimum with the requirements of IEC 62446-1. Additional information identifying plant design and compliance criteria should be documented as well, including:

- Design and site condition parameters
- Applicable codes and standards for the specific location of the plant
- Other design related statutory requirements
- A bill of materials for all major power plant components identifying part numbers, supplier, ratings, and certifications
- A recommended spare parts list
- Justification of design methods where standards or codes are not fully utilized, specifically identifying where designs or equipment:
    - Are not compliant with applicable standards and codes
    - Are compliant with applicable standards and codes, with exceptions
    - Are compliant with equivalent or alternate standards and codes
    - Have no pre-existing basis in available standards and codes
    - Have adequate engineering assessment in lieu of standards
    - Have adequate field evaluation in lieu of factory certifications
- Particular installation procedures where applicable to correctly execute a design
- Design decision or optimization exercises, as applicable, covering topics such as array density, shading, d.c. to a.c. ratio, earthing schemes, lightning protection, a.c. protection coordination, etc.

- Design calculations, simulations and documentation of margins and tolerances for plants with extraordinary site conditions. These would address, for example, locations with high wind regimes, highly corrosive environments, unusual soil conditions, flood zones, etc.

11 Medium and high voltage a.c. systems

11.1 General

The typical PV power plant configuration discussed in this specification includes centralized inverter stations or aggregations of string based inverters with transformers to step voltage up to medium or high voltage levels, such as 12 kV or higher. Plants incorporating string inverters similarly aggregate the output of the inverters at large a.c. switchboards, which in turn are connected to medium voltage transformers. The physical size of large power plants drives the need for the medium or high voltage collection system to deliver power from the inverter-transformer stations to the substation interconnecting the plant to the electric utility.

NOTE High voltage d.c. systems and d.c. to d.c. converter configurations may also be found in PV power plants.

11.2 Selection of a.c. collection system voltage

Common voltage classes used in PV power plant collection systems include:

- 12 kV to 13 kV
- 20 kV to 21 kV
- 25 kV
- 30 kV to 34 kV
- 35 kV to 42 kV

The voltage selected for the plant collection system is determined by location (standard utility specific voltages), the MW capacity of the plant, the internal distances between inverter stations and substation, and the interconnecting utility voltage (if connecting to medium voltage).

NOTE As an approximate guide, the maximum capacity of a single 3-phase circuit operated under normal conditions of use is 10 MVA per every 10 kV. For example, one 34 kV 3-phase circuit is capable of carrying 30 MVA of inverter capacity.

Multiple MV circuits are collected as needed to deliver the full plant capacity to the utility interconnection point or HV substation. Larger plants might require multiple interconnection points to more than one utility substation.

11.3 Collection system configurations

11.3.1 General

Collection systems are most commonly designed as radial or loop configurations. The choice is largely dependent on cost and reliability objectives, which in turn are impacted by the plant size, system voltage, site shape and other variations. Earthing arrangements of the collection system shall comply with IEC 61936.

11.3.2 Radial systems

Radial collection system circuits, or feeders, emanate from a substation or point of interconnection to multiple inverter-transformer stations. The feeder continues to the farthest station served and ends there. Loop fed transformers allow the sequential parallel connection of the inverter stations on a single circuit. This is the least cost design for collection systems. It provides no redundancy for keeping inverter stations interconnected if there is a failure in the line between the substation and the station.

11.3.3 Loop systems

Loop system feeders provide a round trip circuit path between a substation or point of interconnection to multiple inverter-transformer stations. As with radial systems, loop fed transformers allow the sequential parallel connection of the inverter stations on a single circuit. Typically the loop is “open,” meaning two circuits from the substation feed a different set of inverter stations but meet at an open switch. A failure at some location on a feeder allows switches to be reconfigured to pick up as many inverter stations as possible, up to the available capacity of the feeder circuits. This approach is more expensive than radial systems but provides redundancy. Loop systems can also operate in a closed configuration, in which the loop is energized by the utility from both ends. This is not common in PV plants. The marginal reliability improvements that can be gained by closed loop systems typically are not sufficient to justify the cost and complexity of the additional fault protection required.

11.4 Medium or high voltage transformers

11.4.1 Transformer types

The types of transformers used in a PV power plant will vary based on the interconnect voltage, plant location and compliance requirements. In general, liquid-immersed or dry type transformers can be deployed to connect with a MV or HV collection system.

Specialized 3- or 4-winding transformers are commonly used when connecting multiple inverters to the same transformer. This serves the purpose of maintaining galvanic isolation between inverters on the low voltage windings. Design and operation of MV or HV transformers shall follow the standards listed below, as applicable. Transformers shall also comply with any additional requirements specified by the inverter manufacturer, such as impedance values, special harmonic profiles, or load profiles:

- IEC 60296
- IEC 60076-1
- IEC 60076-2
- IEC 60076-3
- IEC 60076-4
- IEC 60076-5
- IEC 60076-7
- IEC 60137
- IEC 60085

The applicable test standards vary based on the type of insulation. Below are some of the applicable IEEE test standards for MV or HV transformers (see Bibliography):

- IEEE C57.12.00-2010
- IEEE C57.154-2012
- IEEE C57.12.90-2010
- IEEE C57.12.91-2011

Apart from the above, local jurisdictions may require compliance to additional test standards. Care shall be taken to ensure that all requirements are met before installing the MV transformer.

11.4.2 Installation

Installation practices for MV or HV transformers can also differ depending on their location and deployment application.

MV or HV transformers, if mounted on pre-designed hollow concrete/steel platforms or in housings, may have bottom entry for the conductors, whereas pad mount transformers can have a side entry option in the enclosure. Proper care shall be taken to specify the transformer manufacturer/supplier to design in accordance to the site requirements. Based on the location of the plant the environmental rating of the MV or HV transformer enclosure can vary. For example, in projects near sea coast, the saline environment can have corrosive effects on the enclosures and eventually the powered equipment.

11.4.3 Protection

For any electrical circuit, consideration shall be made for protection against harmful abnormal conditions. The protection equipment quickly senses the abnormality and signals the device (switchgear) to trip or go off line. MV or HV transformers need to be protected against faults on the grid and internal conditions such as over-temperature, oil-pressure or insulation failures. Relays coordinated with the upstream and downstream protection relays shall be deployed wherever necessary. Thermal magnetic and or numerical relays can be used based on utility specifications. Commonly used protections include but are not limited to over current protection, short circuit protection, ground fault, and over temperature protection. The HV rating of the transformer is determined by the MV or HV grid voltage. The LV rating and the power rating of the transformer are determined by the connected inverter ratings, including the overload capability of the inverter. The impact of harmonics generated by the inverter or power grid shall also be taken into account.

11.5 Medium or high voltage switchgear and stations

11.5.1 General

Medium or high voltage switchgear or junction boxes (sectionalizing cabinets) may be co-located with individual transformers, and/or centralized for aggregation and final interconnection to the utility. The substations are generally located at the perimeter of plants adjacent to public roads, may be fenced off separately, and should allow for access by utility and other contractor vehicles.

11.5.2 Switchgear specifications

MV or HV switchgear shall comply with the following standards:

- IEC 62271-1
- IEC 62271-200
- IEC 62271-100
- IEC 62271-102
- IEC 62271-103

Typically these requirements may be supplemented or modified by national or utility specific requirements, so designers shall be aware of the local conditions.

11.6 Medium voltage cable

Medium or HV voltage cable and its installation shall comply with the following standards:

- IEC 60502-1
- IEC 60502-2
- IEC 60183
- IEC 61238-1
- IEC 61936-1

11.7 Utility interface

Utility interface requirements shall meet local utility, regional, and or national requirements, and to the extent applicable, shall follow the recommendations and requirements of IEC standards published by Technical Committee 8 related to interconnection of renewable based systems.

12 Auxiliary power systems

Auxiliary power systems are the circuits employed to supply power to non-generating equipment at the PV power plant. The design typically involves a cost trade-off analysis of providing a separate system, sometimes metered separately from the PV production, or tapping off of the PV power a.c. output circuits to supply loads locally at inverter-transformer pads. Energy consumption is typically low throughout the field unless significant inverter container cooling is required.

PV field a.c. electrical loads vary from plant to plant. In some plants there are none, but possible loads include:

- AC power to combiner boxes for current monitoring circuits
- AC power to combiner boxes for switch or relay control, including arc-interrupters
- AC power to combiner boxes for security systems
- AC power to tracker motors and controllers
- AC power for enclosure heating and ventilation to prevent condensation and maintain operation and storage temperatures within acceptable range
- AC power to radio communication equipment (cell modems, microwave radio links)
- AC power to other monitoring systems
- AC power to field security lights

In most cases it is possible and recommended to supply these loads with dedicated feeder circuits, combining multiple loads on a single set of supply cables. The individual loads generally have low current and energy requirements.

13 Communications systems

13.1 General

Communication systems shall follow local utility requirements pertaining to compatible protocols, required parameters, and sampling. General communication protocols should meet requirements set forth in:

- IEC 61850
- IEC 60870-5-104

13.2 Data sampling speed requirements

Designs need to address requirements for data sampling. In many PV power plants, high sampling rates (less than 30 s to 1 min) are not required. However, where utility interconnection includes requirements for low-voltage ride through, dynamic voltage or reactive power control, higher speed sampling and polling for example 1 s, is helpful for communication between the metered point of connection with the utility and each of the inverters. Higher rate samples may be used for fault diagnosis in plants interconnected to utility grids that are relatively unstable or otherwise prone to voltage or frequency excursions. Polling speed of a centralized data system is affected by the large number of inverters, so this should be considered. It is important to ensure time-stamp coordination for combined measurements when multiple data sources are employed.

NOTE Specialized metering instruments for permanent or temporary use are sometimes used in coordination with the basic SCADA system to record high-rate data for specific utility fault, ride-through, or harmonics measurements.

Annex A
(informative)

Inverter application considerations in PV power plants

A.1 General

This informative annex provides basic considerations for the use and application of inverters in PV power plants. PV system technology advances at a rapid pace and there will therefore always be exceptions to the generalizations made herein. The annex is intended to provide guidance only with respect to considerations that in practice should be evaluated on a case by case basis.

A.2 Advantages and disadvantages of central inverters

The main advantages of central inverters are:

- Simplified architecture of d.c. distribution circuits throughout the arrays.
- Often a larger range of control options are available with respect to the grid interface.
- Control of these inverters is centralized with respect to the grid.

The disadvantages of central inverter system topologies are found in the system configuration:

- Increased cost in d.c. wiring and protection.
- Independently operating sections of the PV array at their maximum power point (MPP) requires extra hardware on the d.c. side. Mismatch between sections (e.g. caused by partial shading) may therefore significantly reduce the overall system output.
- Monitoring of subsections of the PV array has to be done in separate d.c. monitoring equipment.
- Incremental changes to system size are more difficult.
- Less redundancy than in systems with multiple inverters.

A.3 Advantages and disadvantages of string inverters

The main advantages of string inverters are:

- Simplification of d.c. protection such as for arcing and earth-faults.
- PV array more tolerant to mismatch and shading problems.
- Inverter consolidates more granular monitoring of strings for performance assessment and location of faults.
- Increased redundancy.
- An extension to system size is very modular.
- Breaking down a large array into smaller pieces at the design stage widens the range of inverters that may be available, allowing flexibility in selecting string voltages currents and power ratings for each subsection.

The disadvantages of string inverter topologies are:

- Increased a.c. wiring and protection.
- More complex control when using inverter based features to meet grid-interface requirements.

A.4 Issues affecting inverter size

A.4.1 PV array output

To size an inverter accurately requires an accurate picture of the actual output of the PV array at the installation site.

Analysis of system performance under the full range of environmental conditions experienced at the installation site. The outcome of this analysis is dependent on the accuracy and the detail contained in the data used. The better the accuracy, the wider the period of sampled data covering all seasons and the finer the time step sampling the better the outcome of the analysis.

Data covering a wide range of environmental operating conditions is essential to ensure all possible operating states are covered. The time sampling steps are important because averaged data will mask upper and lower limits of operation and the frequency that these occur. For example if a PV installation is in a site where there are weather patterns that produce regular scattered cloud then there is the strong possibility that cloud focusing will occur frequently which may drive irradiance to very high levels producing high PV output. This on a regular basis may contain significant energy content and will regularly produce high potential currents in the inverter input or the inverter may have to limit input by tracking away from the maximum power point.

The important outputs of this analysis are:

- Maximum array output voltage
- Maximum and minimum MPPT voltage
- Maximum array power
- Maximum array current

A.4.2 Inverter ratings

The inverter shall remain within the maximum voltage, current and power ratings as specified by the manufacturer under all normal and forseeable abnormal environmental conditions.

The inverter shall be able to maximum power point track over the range of operating MPPT voltage of the array.

Inverter efficiency and thermal considerations need to be taken into account for the environment where the inverter is installed including any enclosure requirements.

The altitude impact on inverter rating needs to be considered (cooling capacity and switching device voltage capabilities are reduced in the thinner air).

A.4.3 Inverter output control requirements

When sizing an inverter it is also important to consider any extra utility a.c. control requirements that may affect the inverter rating such as reactive power control. It is important to consider the time that reactive power control is required with respect to inverter real array power output requirements. If the inverter is required to output significant reactive power during maximum PV array output the output rating of the inverter will need to be increased.

A.4.4 PV power to inverter power ratio (PVIR)

PVIR = PV nominal maximum power at STC/Inverter maximum a.c. output power

PV power plants are often designed with high PVIR ratios to achieve lower installed cost of energy. From a technical standpoint, it is most important to consider the PVIR impact on the safe operation of the inverter. If the PVIR is too high the input rating of the inverter may be exceeded depending on the inverter manufacturer's specification of the input.

When assessing the maximum inverter ratings the PV peak power available at the project site, the peak irradiance and the temperature at the time of peak irradiance should be considered in calculating the maximum power output of the PV array.

A high PVIR will mean:

- the inverter will operate in current limiting mode for longer periods
- more constant power output over an extended period of the day (during current limiting)
- potentially high efficiency for longer periods of the day
- higher operating temperatures for longer periods and thermal considerations need to be carefully examined. The de-rating of the power of inverter output versus temperature may be impacted when PVIR is high
- a potential impact on the ability of the inverter to stay within its MPP range in cold, high irradiance conditions (If the operating voltage window does not have a high enough upper limit the inverter will shut-down while attempting to limit current)
- a potential impact on sub-array d.c. fuse ratings (if Isc with multipliers exceeds the max input fuse ratings of the inverter).

A low PVIR will mean:

- longer operating periods at lower inverter output power as a percentage of rating, and hence potentially lower efficiency
- inverter will capture more of high peak PV output
- Inverter will capture less of available low irradiance production.

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