TECHNICAL APPLICATION PAPER

Photovoltaic plants

Cutting edge technology.
From sun to socket

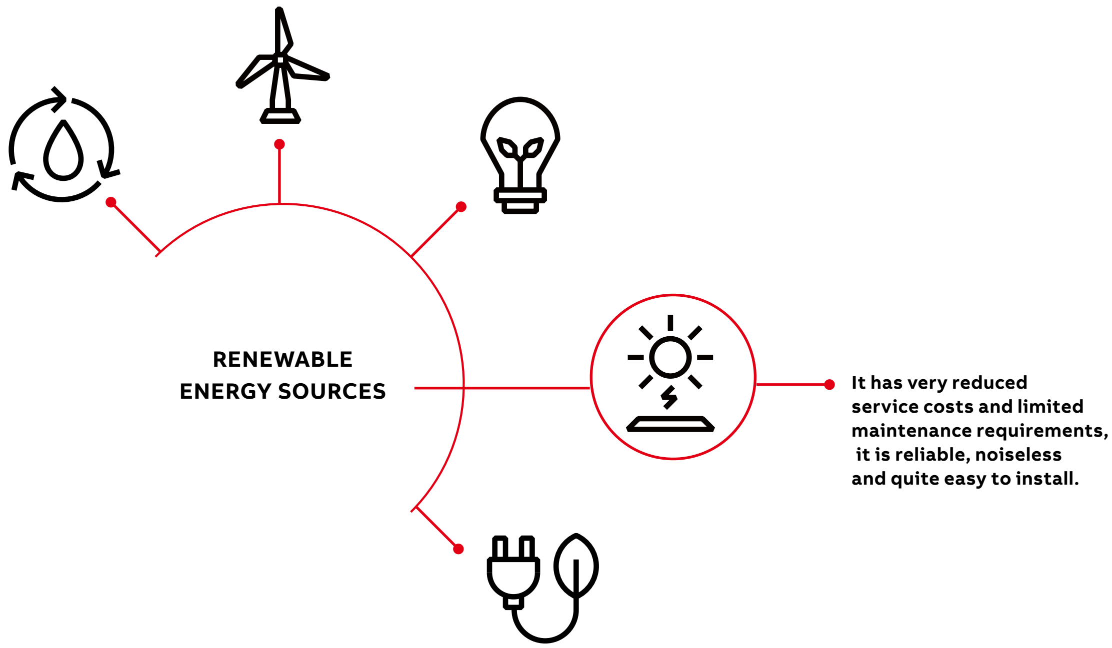
Introduction

In the present global energy and environmental context, the aim to reduce the emissions of greenhouse gases and polluting substances (also following the Kyoto protocol) has become of primary importance. This target can be reached also by exploiting alternative and renewable energy sources to back up and reduce the use of the fossil fuels, which moreover are doomed to run out because of the great consumption by several countries.

The Sun is certainly a high potential source for renewable energy and it is possible to turn to it in the full respect of the environment.
Just think that instant by instant the surface of the terrestrial hemisphere exposed to the Sun gets a power exceeding 50 thousand TW; the quantity of solar energy which reaches the terrestrial soil is enormous, about 10 thousand times the energy used all over the world.

Among the different systems using renewable energy sources, photovoltaics is promising due to the intrinsic qualities of the system itself: it has very reduced service costs (fuel is free of charge) and limited maintenance requirements, it is reliable, noiseless and quite easy to install.

Moreover, photovoltaics, in some grid-off applications, is definitely convenient in comparison with other energy sources, especially in those places which are difficult and uneconomic to reach with traditional electrification.



—
01 Residential PV plant
—
02 Industrial/commercial roof top PV system
—
03 PV system on carport
—
04 Utility scale PV system

This Technical Paper is aimed at introducing the basic concepts to be faced when realizing a photovoltaic plant.

Starting from a general description of the main components of a PV Plant, the main design concepts of the PV field and the inverter selection criteria were described. The methods of protection against indirect contact, overcurrents, and overvoltages were also introduced in order to guide the designer in the correct design of the PV plant according to the standards requirements.

This new edition of the Technical Paper takes in consideration all the Standards that represent the state of the art.

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01

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Technical Application Paper Photovoltaic plants

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Generalities on photovoltaic (PV) plants

Generalities on photovoltaic (PV) plants

1.1 Types of photovoltaic plants

PV systems can be very simple, consisting of just a PV module and load. However, depending on the system configuration, we can distinguish three main types of PV systems:

- **Grid connected**
  (also called On Grid or Utility Interactive System):
  this type of PV systems is always connected to the grid. The power that the PV generator produce is converted by the inverter from DC to AC and after that the energy is fed to the grid. During times when there is no sunlight, the loads consume the grid's electricity.

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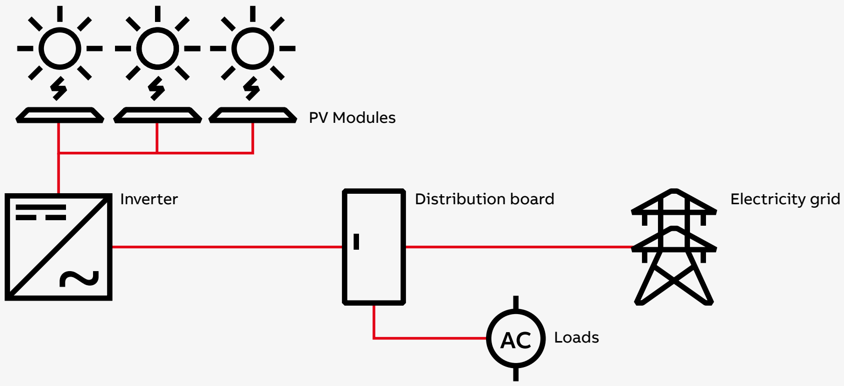
Figure 1



- **Off Grid System**
  (also called a Stand-Alone System):
  Off grid solar systems or stand-alone systems are not connected to the grid. The PV system produce electricity, which is stored in the battery banks. During nights, this stored electricity is used to provide power. The stand-alone systems are common in the remote areas where there is no electricity and no grid access.

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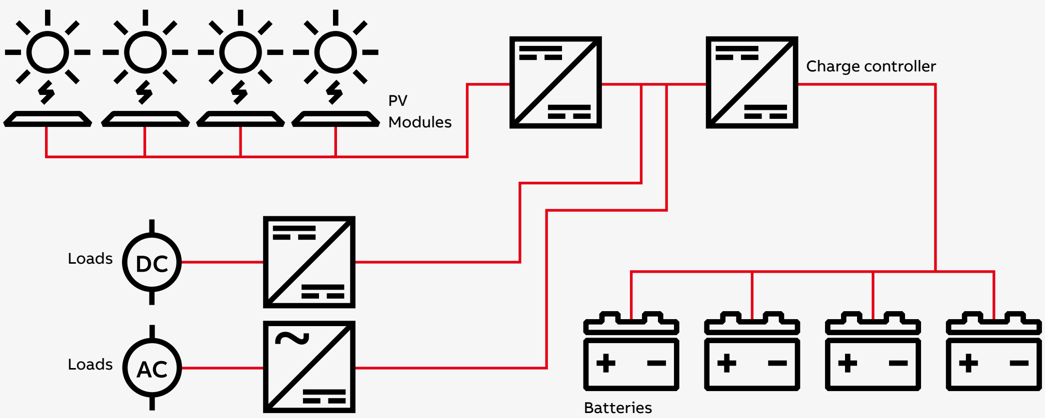
Figure 2



- **Solar Hybrid System:**
  Hybrid solar systems are configurated to have an automatic disconnect switch which could toggle on or off depending upon electricity requirements of the micro-grid where the PV systems are connected.

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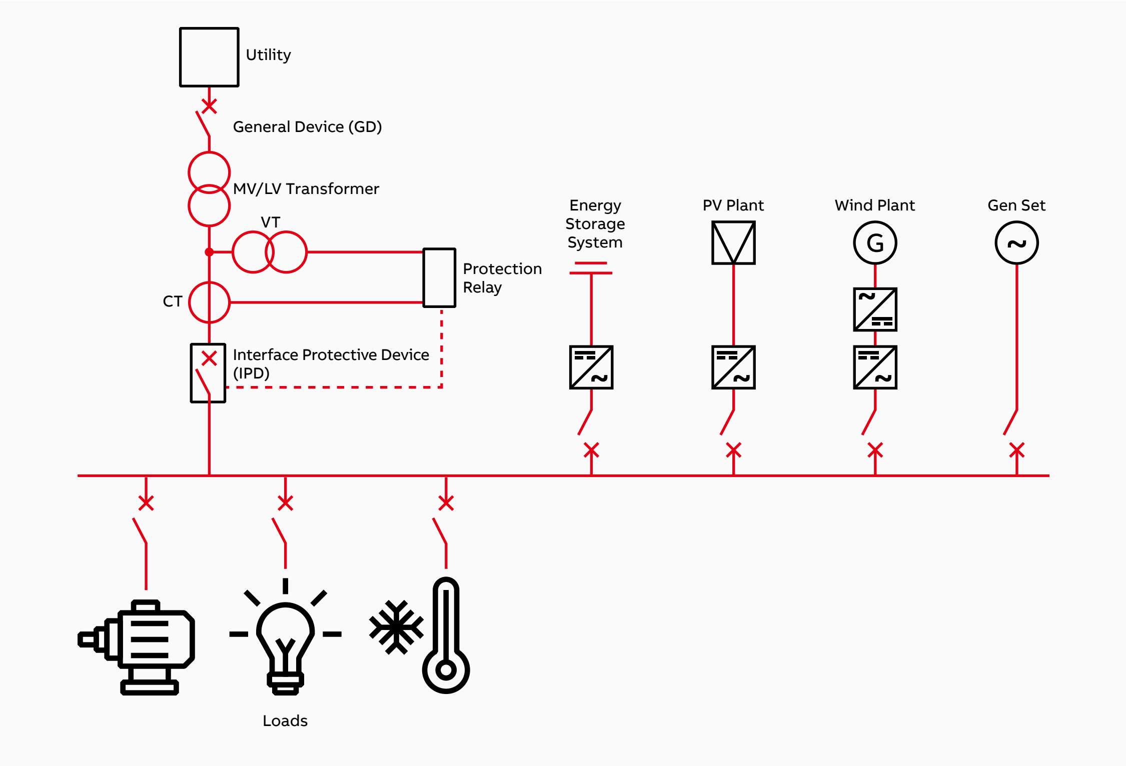
Figure 3



1.2 Main components of a photovoltaic plant

1.2.1 Photovoltaic generator

The photovoltaic cell is the most elementary photovoltaic device[1]. A photovoltaic module[2] is a group of interconnected photovoltaic cells environmentally protected. The PV arrays are mechanical and electrical assemblies of photovoltaic modules (a photovoltaic array includes all components up to the DC input terminals of the inverter or other power conversion equipment or DC loads). The photovoltaic generator is a generator that uses the photovoltaic effect to convert sunlight into electricity and it is represented by the PV array in a PV system.

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1
IEC 61836 TS Solar photovoltaic energy systems - Terms, definitions and symbols

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2
Module ≠Panel; Photovoltaic modules can be assembled into photovoltaic panels; PV panel is composed by PV modules mechanically integrated, pre-assembled and electrically interconnected

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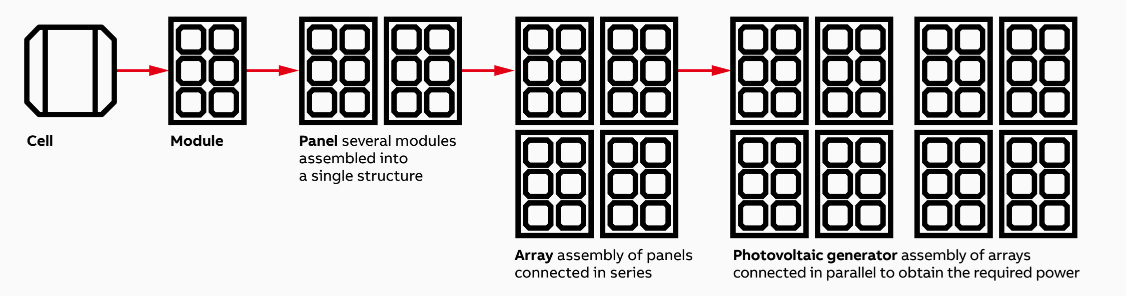
Figure 4



To better understand the behaviour and the composition of the PV generator is necessary to clarify the behaviour of series and parallel interconnection of cells or modules.

In a series connection of cells / modules:
- the voltages add up;
- the current does not add up: it is determined by the photocurrent in each solar cell. The total current in a string of solar cells/modules is equal to the current generated by one single solar cell.

The PV modules string is a circuit of series-connected PV modules. The photovoltaic string combiner box is an enclosure where photovoltaic strings are electrically connected in parallel and where protection devices may be located if necessary.

Example 1
- The open circuit voltage (V_{oc}) of one cell is equal to 0.6 V; a string of 3 cells will deliver an open circuit voltage (V_{oc}) of 1.8 V.
- The short-circuit current (I_{sc}) of a 6” monocrystalline cell is equal to 9.97 A; a string of 3 cells will deliver short-circuit current (I_{sc}) of 9.97 A.
- The open circuit voltage (V_{oc}) of one module (e.g. 60 monocrystalline 6” cells rated 300 W at STC conditions) is 39.4 V; a string of 20 modules will deliver an open circuit voltage (V_{oc}) of 788 V.
- The short-circuit current (I_{sc}) of one module (e.g. 60 monocrystalline 6” cells rated 300 W at STC conditions) is equal to 9.97 A; a string of 20 modules will deliver short-circuit current (I_{sc}) of 9.97 A.

In a parallel connection of cells / modules:
- the voltage is the same over all solar cells/modules;
- the currents of the solar cells/modules add up.

Example 2
- The open circuit voltage (V_{oc}) of one cell is equal to 0.6 V; the parallel of 3 cells will deliver an open circuit voltage (V_{oc}) of 0.6 V.
- The short-circuit current (I_{sc}) of a 6” monocrystalline cell is equal to 9.97 A; the parallel of 3 cells will deliver short-circuit current (I_{sc}) of 29.91 A.
- The open circuit voltage (V_{oc}) of one module (e.g. 60 monocrystalline 6” cells rated 300 W at STC conditions) is 39.4 V; the parallel of 3 modules will deliver an open circuit voltage (V_{oc}) of 39.4 V.
- The short-circuit current (I_{sc}) of one module (e.g. 60 monocrystalline 6” cells rated 300 W at STC conditions) is equal to 9.97 A; the parallel of 3 modules will deliver short-circuit current (I_{sc}) of 29.91 A.
- The open circuit voltage (V_{oc}) of a string of 20 module (e.g. 60 monocrystalline 6” cells rated 300 W at STC conditions) is 788 V; the parallel of 3 strings will deliver an open circuit voltage (V_{oc}) of 788 V.
- The short-circuit current (I_{sc}) of a string of 20 module (e.g. 60 monocrystalline 6” cells rated 300 W at STC conditions) is equal to 9.97 A; the parallel of 3 strings will deliver short-circuit current (I_{sc}) of 29.91 A.

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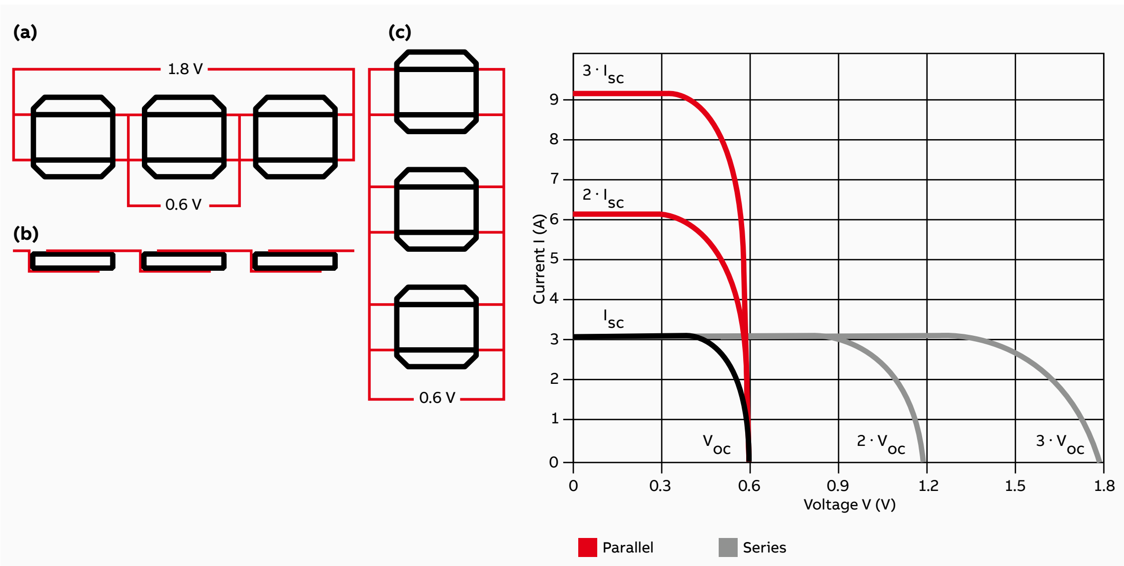
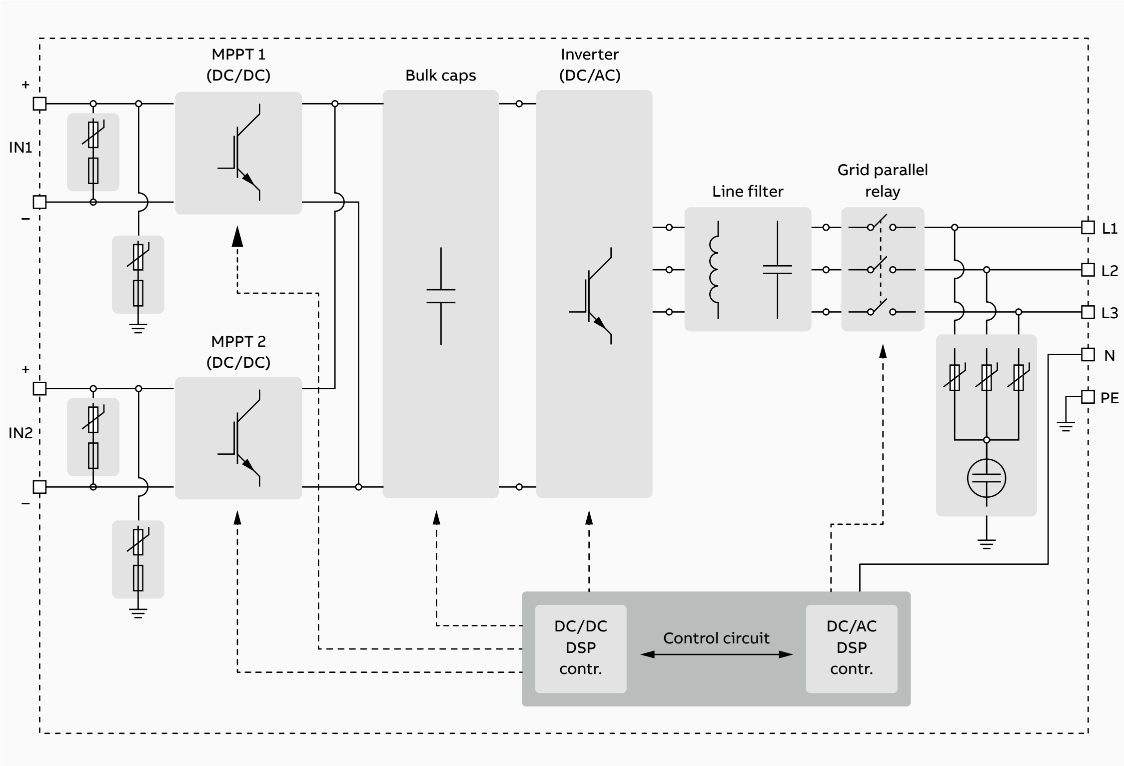
Figure 5



1.2.2 Inverter

The inverter is the equipment that converts direct current to alternating current and controls the quality of the output power to be delivered to the grid.

Figure 6



The main parts that compose the inverters are (Figure 6):

- **MPPT** (Max power point tracker): it is a circuit (typically a DC to DC converter) employed in the photovoltaic inverters in order to maximize the energy available from the photovoltaic generator at any time during its operation. The power delivered by a PV generator depends on the point where it operates. Controllers can follow several strategies to optimize the power output of the photovoltaic generator. MPPT may implement different algorithms (e.g. Perturb and observe, Current sweep, Incremental conductance, Constant voltage, etc.) and switch between them based on the operating conditions of the photovoltaic generator.
- **Bulk capacitors**: Bulk Capacitors are used to prevent ripple currents from reaching back to the DC power source, and to smooth out DC bus voltage variations. They are also used to protect IGBTs.
- **DC/AC inverter**: the inverter is a circuit which converts a DC power into an AC power at desired output voltage and frequency. This conversion can be achieved by controlled turn on and turnoff devices (e.g. IGBT). The output voltage waveform of an ideal inverter should be sinusoidal. However, the voltage waveforms of the inverters are non-perfectly sinusoidal and contain harmonics. The output frequency of an inverter is determined by the rate at which the semiconductor devices are switched on and off by the inverter control circuitry. To obtain a waveform as sinusoidal as possible, a more sophisticated technique – Pulse Width Modulation (PWM) – is used; PWM technique allows a regulation to be achieved on the frequency as well as on the r.m.s. value of the output waveform.
- **Line filter**: usually it is a L-C filter used in order to controls the quality of the output power to be delivered to the grid; the use of LC filter allows for generation of sinusoidal voltages with low harmonic distortion.

Moreover, due to the characteristics of the required performances, the inverters for off-grid plants and for grid-connected plants shall have different characteristics:

- in off-grid plants the inverters shall be able to supply a voltage on the AC side as constant as possible at the varying of the production of the generator and of the load demand;
- in grid-connected plants the inverters shall reproduce, as exactly as possible, the network voltage and at the same time try to optimize and maximize the power output of the PV modules. The inverters are equipped with protection that control the synchronization of the inverter to the grid parameters.

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1.2.2.1 Centralized inverters

Central inverters are inverters up to 5000 kW (this up limit is growing continuously). The central inverter solutions can be used in PV power plants of commercial and industrial buildings and usually in ground mounted applications. The PV plant architecture with centralized inverter is described in Figure 7; this architecture requires the use of DC combiner boxes for the parallel of the PV strings.

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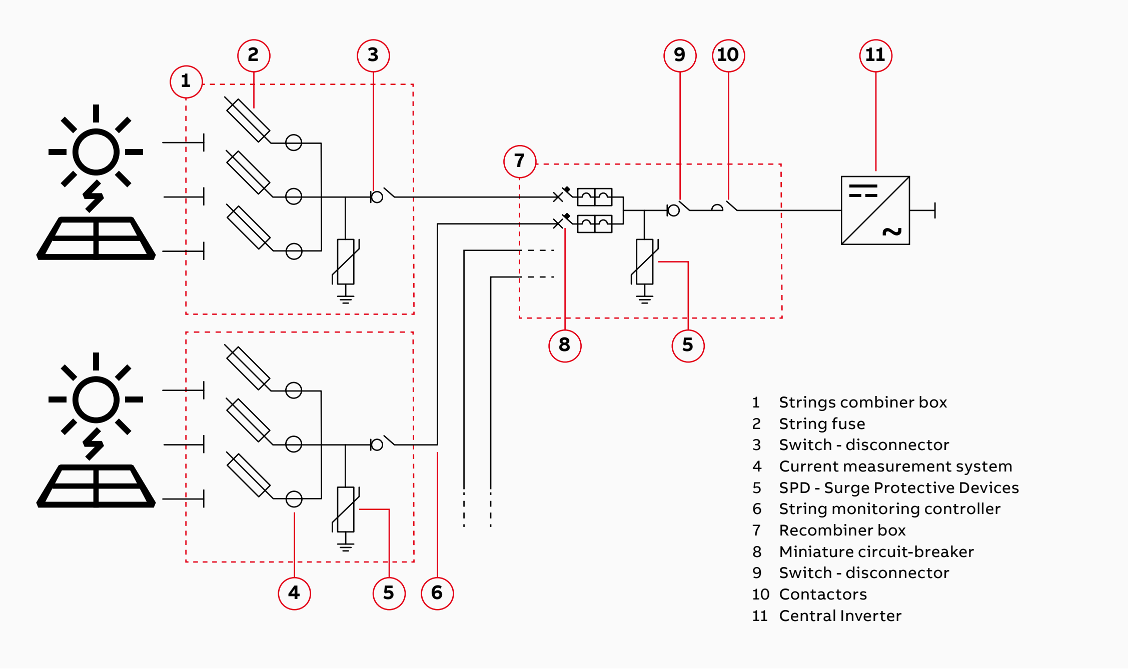
Figure 7



The features and benefits of central inverters are:
- lower CAPEX;
- reduced number of inverters;
- more experience with on-field applications.

1.2.2.2 String inverters

String inverters are inverters from 1.2 kW to 175 kW. The string inverter solutions can be used usually in PV power plants of residential, commercial and industrial buildings as well as in ground mounted applications. The PV plant architecture with string inverter is described in Figure 8.

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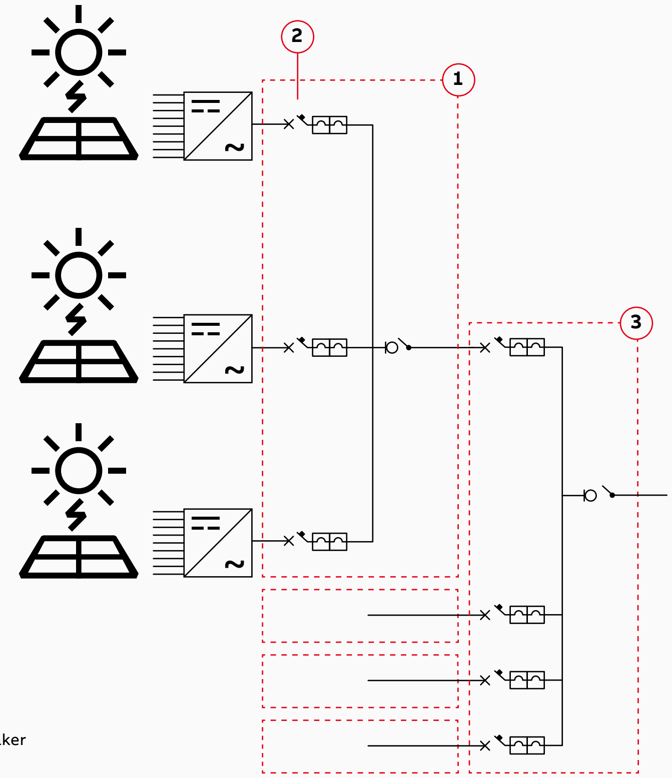
Figure 8



1 AC combiner box
2 Miniature circuit-breaker
3 AC Recombiner box

The features and benefits of strings inverters are:
- configurable all-in-one design with built-in and monitored DC input protection devices;
- wide input voltage range;
- multiple MPPT inputs;
- high total efficiency;
- advanced grid support functions;
- safe and intuitive user and service interface;
- suitable for outdoor and indoor installation;
- minimum maintenance loss (maximum uptime);
- simple fault finding;
- better OPEX;
- easier logistics;
- direct connection of the strings inside the inverter.

1.2.2.3 Microinverters

Microinverters are installed behind 1 or few PV modules and convert the DC power from PV modules to grid-compliant AC power right at the module. The microinverter solutions can be used in PV power plants of residential and commercial buildings. The PV plant architecture with microinverter is described in Figure 9.

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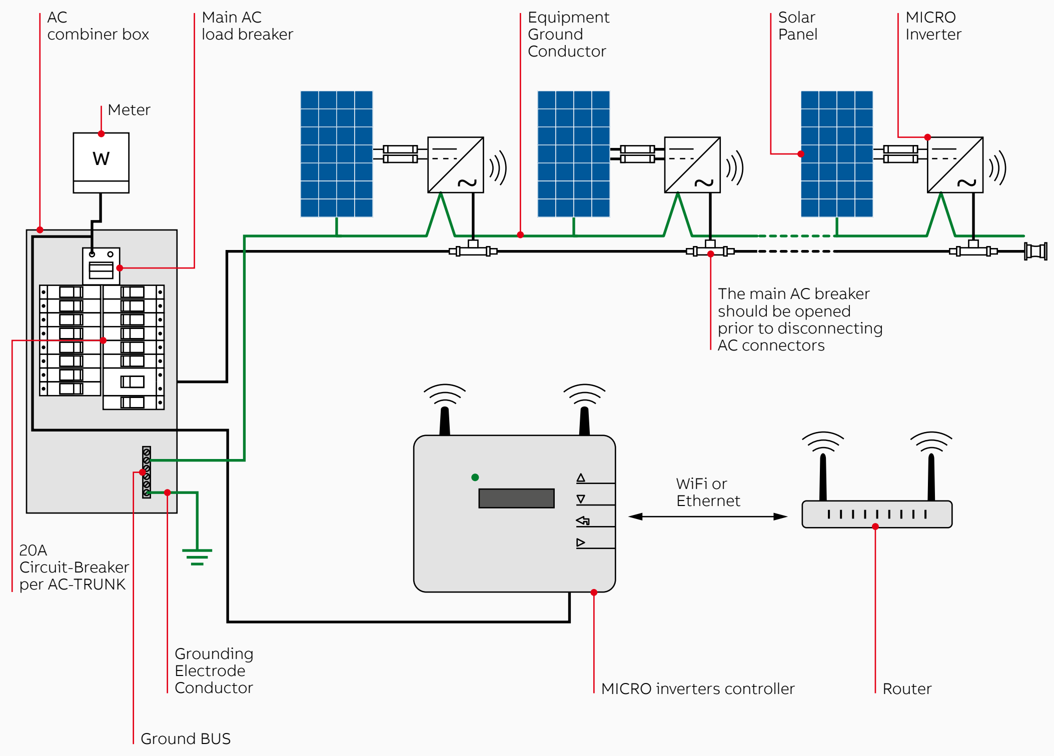
Figure 9



Note: All numbers are rated, manufactures' specifications, or nominal unless otherwise specified.
WEEB grounding clips were used between modules and rails; the only ground wire is between the rails and from the rails to ground rod.

The advantages of micro-inverters are:
- reduce power loss in case of shadow;
- minimum maintenance loss;
- single PV module performance monitoring;
- smaller Cable Size (Since output is converted from DC to AC (230V) at the back of the panel, the cable required to carry the current can be of lower diameter).
- PV plant high modularity;
- single module shutoff in case of emergency.

However, the PV plant with microinverter architecture have a higher initial cost.

1.2.2.4 Inverter Architecture Choice

The choice of inverter architecture impact on PV plant costs. Over the last few years the costs of central and string inverters have closed dramatically. The cost of string inverters is still higher than central inverters (CAPEX Material Analysis).
The installation cost is also a driver for the choice of the inverter architecture: the mechanical installation, the electrical installation and the commissioning of string inverter is more expensive than that of the central inverters.
The DC BOS is more expensive for central inverter architecture and the AC BOS is more expensive for string inverters architecture. On a global level, the installation cost of string inverters is higher than that of centralized inverters.

The main difference between central and string inverters originates from operating costs:
- The large power capacity of central inverters leads to the need for active cooling. The smaller capacity of string inverters eliminates the need for active cooling.
- Central inverter cabinets are constructed with fans, filters, and vents to allowing cooling: these components require maintenance. Moreover, the power conversion unit and the control boards may need to be replaced during the expected life of the inverter. The central inverter is designed to be serviced in the field and then the maintenance costs are considerable. The string inverters usually are not designed to be field serviceable and then the maintenance costs are low.

From the plant performance point of view:
- The string inverters architecture is characterized by multiple MPPT: if the performance across arrays varies due to non-uniform shading, arrays with different tilt angles or orientations, or damaged modules, the performance of each photovoltaic generator can be optimized at the array level such that output of the system is maximized. Usually the centralized inverter architecture is characterized by a single MPPT.
- Plant availability or “uptime” for central inverter architecture is lower that of the string inverter architecture: if a central inverter goes offline, a significant portion of the photovoltaic generator is lost until functionality is restored. The distributed nature of the string inverter architecture, meanwhile, results in only a small number of arrays going offline if an inverter goes offline.

1.3 Types of photovoltaic modules

1.3.1 Crystal silicon modules

Crystalline silicon modules (c-Si) are nowadays still the most used in the installed PV plants.
The differentiation between different kind of c-Si PV modules could be done according to different criteria mainly focused on the cells characteristics:

- Silicon crystallization: according to the production technology of the ingots the c-Si solar cells could be **monocrystalline** or **polycrystalline**; the monocrystalline solar cells are made from a pure form of silicon. The polycrystalline solar cells are obtained from casted ingots where the crystals have not perfectly the same orientation.
- Cells geometry: the cells geometry depends mainly from the silicon ingots production technology. The cells could be **square** or **semi-square**; usually the monocrystalline solar cells could be semi-square or square and the polycrystalline solar cells could be square.

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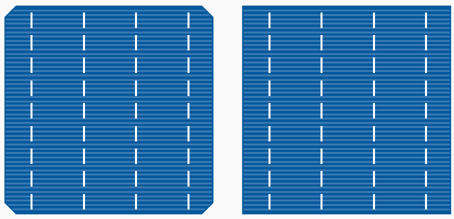
Figure 10
in the left side a semi-square monocrystalline solar cell; in the right side a Square polycrystalline solar cell



- Cells dimension: the cells dimensions depend mainly from the silicon ingot used for the wafer production. Then the cells are categorized in 5” (inch) solar cells and 6” (inch) solar cells.

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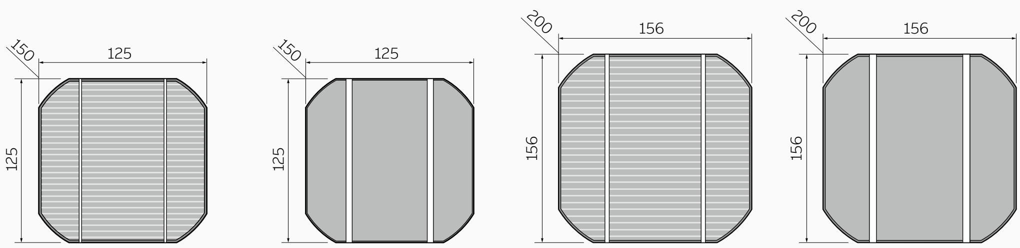
Figure 11
in the left side a 5” semi-square monocrystalline solar cell; in the right side a 6” semi-square monocrystalline solar cell



- Nowadays the most common cells are 6”; the height and the width of a 6” solar cells **156 mm** or **156.75 mm**. The semi-square cells are characterized also from the diagonal of the cells that could be **200 mm** or **210 mm**.

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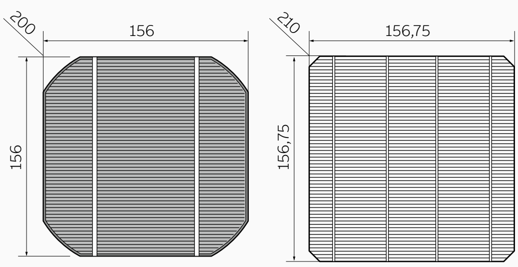
Figure 12
in the left side a 6” semi-square monocrystalline solar cell 156 x 156 with diagonal 200 mm; in the right a 6” semi-square monocrystalline solar cell 156.75 x 156.75 with diagonal 210 mm.



- Number of busbars: the c-Si solar cells have some contacts screen-printed on the front an on the back side of the cells with metal serigraphic pastes. These contacts on the front and on the back side of the cells are used to make the series cells interconnections. The busbars are the number of main contact screen-printed. Over time the number of busbars has increased in order to reduce the series resistance and the interconnection tabbing ribbons size; until around 3 years ago the most common cells screen-printing configurations were with **2 or 3 busbars**. Nowadays the most common cells screen-printing configurations are with **4 or 5 busbars**.

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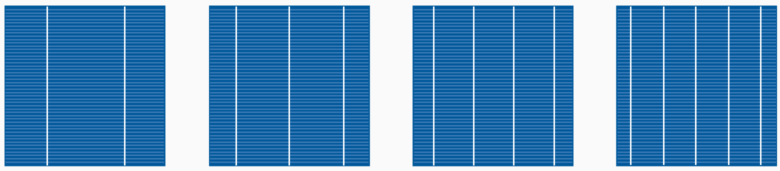
Figure 13
from left to right:
2BB 6” polycrystalline solar cell;
3BB 6” polycrystalline solar cell;
4BB 6” polycrystalline solar cell;
5BB 6” polycrystalline solar cell



- Half or full cell: in a traditional c-Si PV module, the tabbing ribbons that interconnect the neighbouring cells can cause a significant loss of power. The power loss is linked to the current generated by the cells. The current generated by the cells for photovoltaic effect is proportional to the cells dimensions. Cutting solar cells in half has been proven to be an effective way to lower resistive power loss. The **half-cut cells** generate half the current of a **standard cell**, reducing resistive losses in the interconnection of solar modules. Less resistance between the cells increases the power output of a module, depending on the design, of a 2%.

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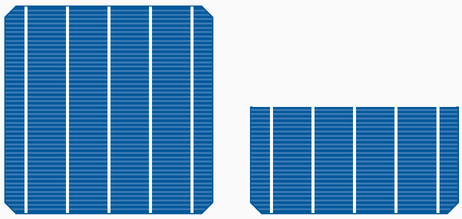
Figure 14
left site: standard cells;
right site: half-cut cells



Other benefits introduced by half-cut cells are:
- better behaviour of module in case of shadow;
- reduced bypass diode activation;
- better protection against micro-cracks;
- cooler hot spots;
- optical gains from larger cell spacing.

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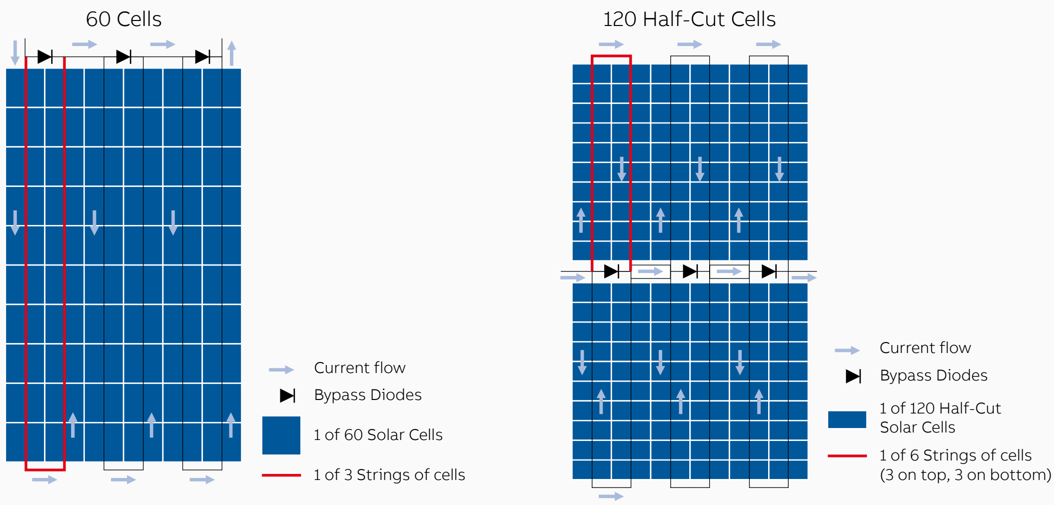
Figure 15
left site: cells interconnection in a module built with standard cells;
right site: cells interconnection in a module built with half-cut cells



- Type of junction: the term **p-type** refers to the fact that the cell is built on a positively charged (hence p-type) silicon base. Indeed, the wafer is doped with boron, which has one electron less than silicium. The top of the wafer is then negatively doped (n-type) with phosphorous, which has one electron more than silicium. This helps form the p-n junction that will enable the flow of electricity in the cell. n-type solar cells are built the other way around, with the n-type doped side serving as the basis of the solar cell. At the moment p-type solar cells are more common because the process of fabrication of n-type solar cells includes more steps and then more costs. By the way most powerful solar cells today available on the market are **n-type** and n-type solar cells are immune to some degradation effect (e.g. LID - Light Induced Degradation). According to this scenario the technology roadmap is moving on n-type.

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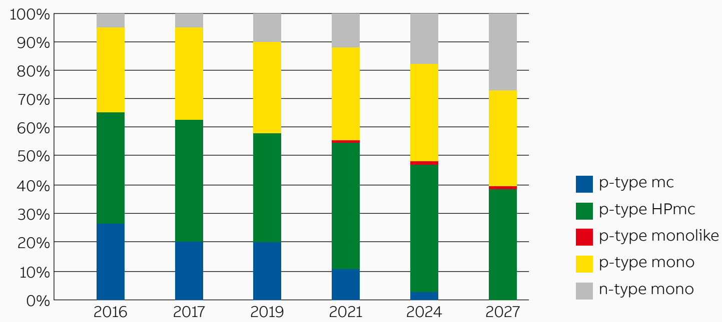
Figure 16
source International Technology Roadmap for Photovoltaic Results 2017



- N° of junction: the traditional c-Si cells are **single-junction** solar cells (single p-n junction). **Multi-junction** (MJ) solar cells are solar cells with multiple p–n junctions made of different semiconductor materials. **Heterojunction** technology (HJT) is a type of Multi-junction and it combines n-type c-Si wafers with amorphous silicon layer. The benefits introduced by the Multijunction in the PV module are:
  - High light yield (the light spectrum that is absorbed by the HJT cells is wider that light spectrum absorbed by a standard c-Si cell);
  - Low temperature coefficient;
  - Higher efficiency.

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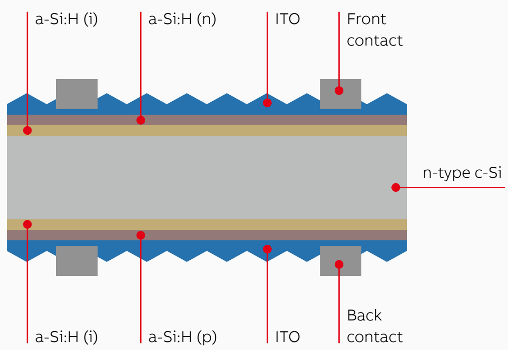
Figure 17
HJT cell stratigraphy; source meyerburger.com



- Mono-facial or bi-facial cell: until few years ago the PV cells were only designed as **mono-facial** and then they were able to collect the solar radiation only on the front of the cell. The technology development introduced the **bi-facial** solar cells. The bi-facial solar cells are able to collect solar radiation also from the back side and then the bi-facial modules are able to collect the reflected solar radiation.

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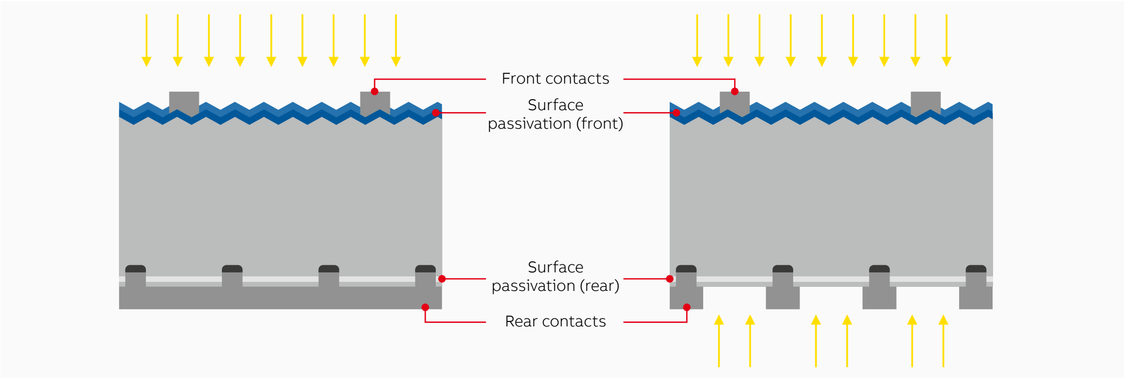
Figure 18
left side a standard mono facial cell; right side a bifacial solar cell



The bi-facial modules are able to increase the energy yield of the PV installation.
The albedo of the surface under the system, one of the decisive factors influencing the amount of the additional energy yield, changes in the field over time. Albedo describes the extent to which light is reflected from a surface. Therefore, the albedo itself depends on the properties of the surface under the module such as colour, thickness, surface finish or type of vegetation.

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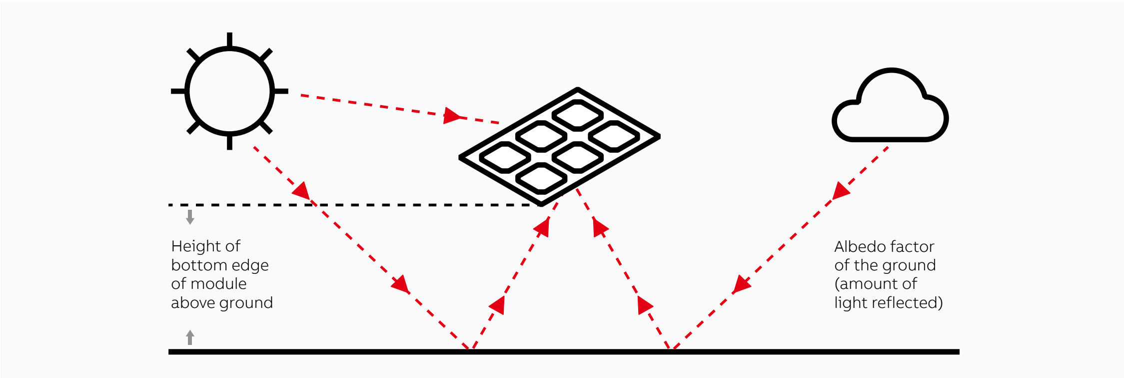
Figure 19
bifacial modules behaviour



The energy gain that bifacial modules generate compared to mono-facial modules is estimated around +5% with modules installed on grass, +10% with modules installed on sand and +20% with modules installed on white-painted surface.

The c-Si PV module most common layouts are:
- 60 6” cells in series connection;
- 72 6” cells in series connection;
- 120 half-cut cells.

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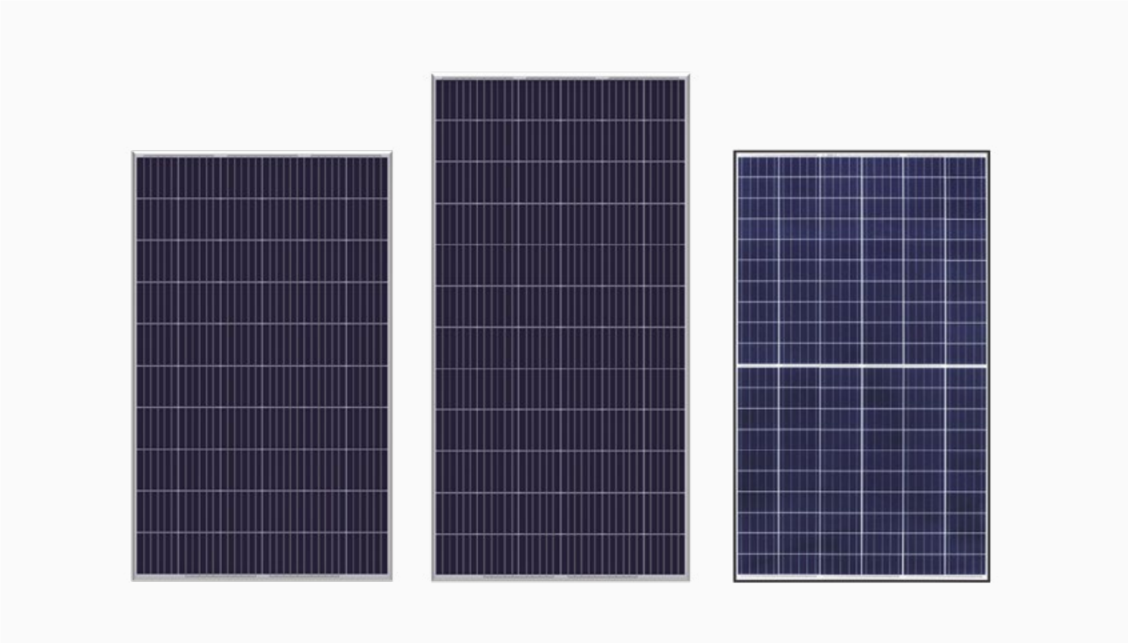
Figure 20
from left to right:
60 6” cells in series connection;
72 6” cells in series connection;
120 half-cut cells.



In order to maximize the performance of the PV module, special technologies have been developed using the concept of **rear contact solar cells**. Rear contact solar cells achieve potentially higher efficiency by moving all or part of the front contact grids in the back side of the cells: the sunny side of the cells is not covered by metal paste for contacts purpose. There are several configurations of rear contact solar cells:
- Interdigitated back contact solar cells (IBC);
- Emitter wrap through (EWT);
- Metallization wrap through (MWT).

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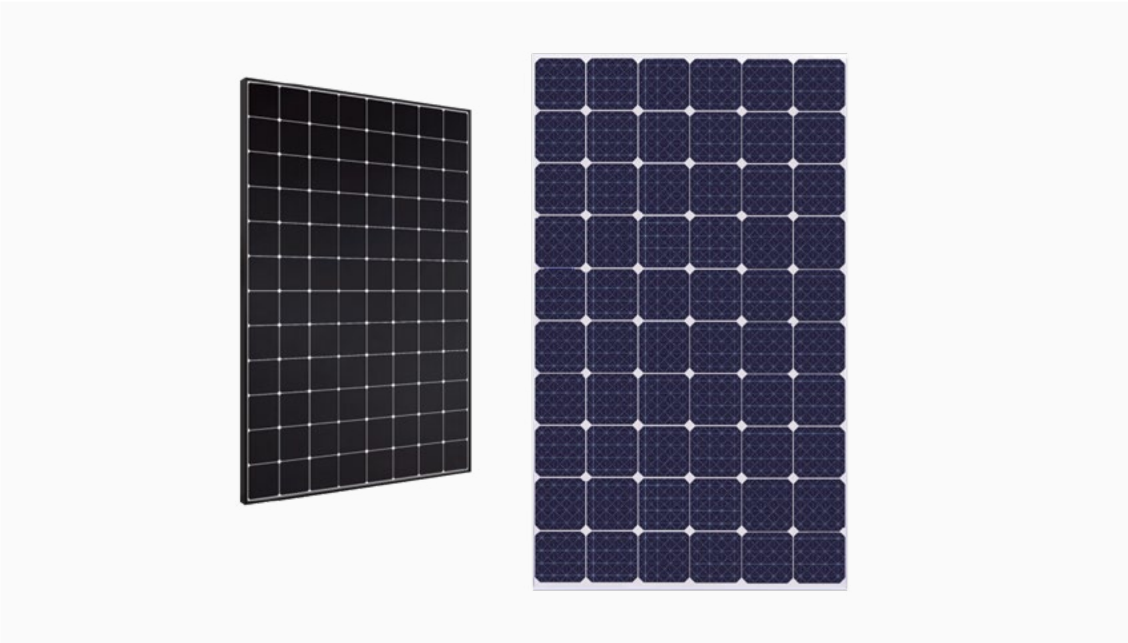
Figure 21
from left to right:
PV module with IBC technology;
PV module with MWT technology.



1.3.2 Thin-film modules

Thin film cells are composed by semiconducting material deposited, usually as gas mixtures, on supports as glass, polymers, aluminium, which give physical consistency to the mixture.
The semiconductor film layer is a few µm in thickness with respect to crystalline silicon cells which are some hundreds µm.

The materials mainly used are:
- amorphous silicon (a-Si);
- cadmium telluride (CdTe);
- indium diselenide and copper alloys (CIS, CIGS, CIGSS);
- gallium arsenide (GaAs);
- dye-sensitized solar cell (DSC).

In the past the PV production chain invested a lot on the thin films technologies because they were offering excellent prospects for cost reduction. By the way, the impressive cost reduction on the c-Si technologies reduced the investments on the thin films.
Nowadays the thin-film technology that still have a good market share is the CdTe technology.

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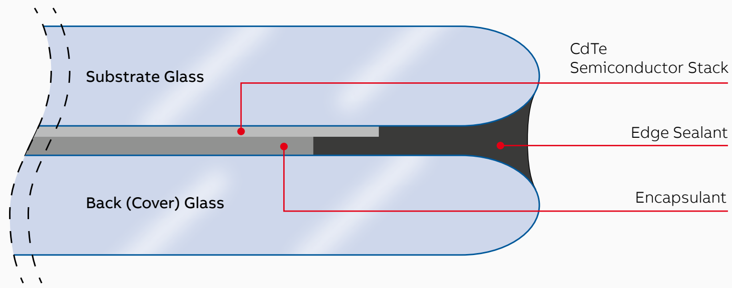
Figure 22
Cross section of CdTe PV module



Often the thin film modules have glass as front-sheet and also as back-sheet and then they are frameless.

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Figure 23
CdTe PV module

Some thin film technologies are really interesting because they are deposited on flexible support, usually polymer films. In comparison with c-Si modules, thin film modules show a lower dependence of efficiency on the operating temperature and a good response also when the diffused light is more marked and the radiation levels are low, above all on cloudy days. The thin-film modules installation is recommendable in the areas with really high temperature (arid climate areas).

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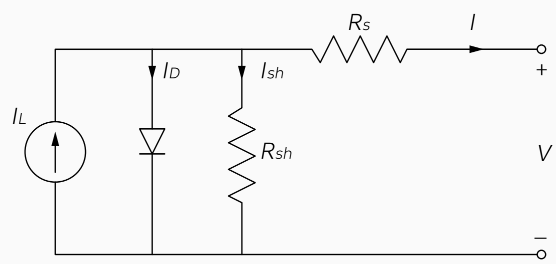
Energy production

Energy production

2.1 Circuit equivalent to the cell

A photovoltaic cell can be considered as a current generator and can be represented by the equivalent circuit of Figure 24.

Figure 24



The current I at the outgoing terminals is equal to the current generated through the PV effect I_L by the ideal current generator. It decreases by the diode current I_D and by leakage current lost due to shunt resistances I_{sh}: the leakage current is caused by the current through local defects in the junction or due to the shunts at the edges of solar cells (R_{sh} represents the shunt resistance).
The resistance series R_s represents the internal resistance to the flow of generated current and depends on the thick of the junction P-N, on the present impurities and on the contact resistances.
In an ideal cell, we would have R_s=0 and R_{sh}=∞. On the contrary, in a high-quality silicon cell we have R_s=0.05÷0.10Ω and R_{sh} =300÷400 kΩ. The conversion efficiency of the PV cell is greatly affected also by a small variation of R_s, whereas it is much less affected by a variation of R_{sh}.
The governing equation for the equivalent circuit (Figure 24) is formulated using Kirchoff's current law for current I:

Equation 1

$$I = I_L - I_D - I_{sh}$$

Where:
I_L is the light-generated current in the cell;
I_D is the voltage-dependent current lost to recombination;
I_{sh} is the current lost due to shunt resistances.

In the equivalent circuit with single diode model, I_D is modelled using the Shockley equation for an ideal diode.

—
Equation 2

$$I_D = I_0 \cdot \left[e^{\left(\frac{V + I \cdot R_S}{n \cdot V_T}\right)} - 1 \right]$$

Where:
n is the diode ideality factor (unitless, usually between 1 and 2 for a single junction cell);
I_0 is the saturation current;
V_T is the thermal voltage given by:

—
Equation 3

$$V_T = \frac{k \cdot T_c}{q}$$

Where:
k is Boltzmann's constant ($1.381 \cdot 10^{-23}$ J/K);
T_c is the absolute temperature in K degree;
q is the charge of the electron ($1.6 \cdot 10^{-19}$ C)

Then, the current supplied to the load is given by:

—
Equation 4

$$I = I_L - I_0 \cdot \left[e^{\left(\frac{V + I \cdot R_S}{n \cdot V_T}\right)} - 1 \right] - \frac{V + I \cdot R_S}{R_{sh}}$$

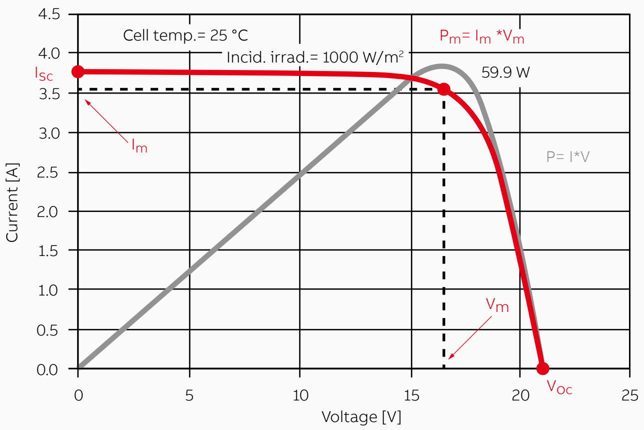
In the usual cells, the last term of this formula, i.e. the leakage current to earth I_{sh}, is negligible with respect to the other two currents. Therefore, the saturation current of the diode can be experimentally determined by applying the open circuit V_{oc} to a not-illuminated cell and measuring the current flowing inside the cell.

2

2.2 Voltage-current characteristic of the module

The voltage-current characteristic curve of a PV module is shown in Figure 25. Under shortcircuit conditions the generated current is at the highest (I_{sc}), whereas, with the circuit open, the voltage (V_{oc}=open circuit voltage) is at the highest. Under the two above mentioned conditions, the electric power produced in the cell is null, whereas under all the other conditions, when the voltage increases, the produced power rises too: at first, it reaches the maximum power point (P_m) and then it falls suddenly near to the open circuit voltage value.

— Figure 25

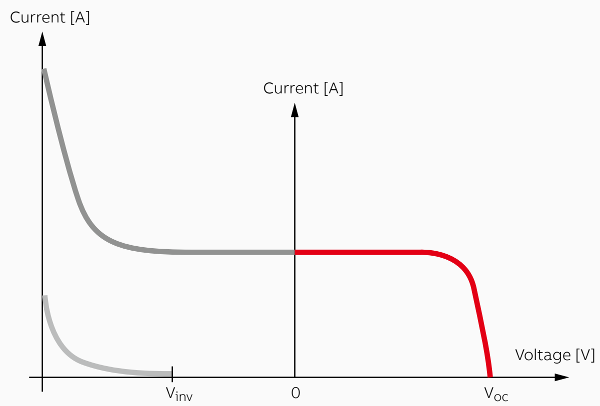


Then, the characteristic data of a PV module can be summarized as follows:

- I_{sc} short circuit current;
- V_{oc} open circuit voltage;
- P_m or P_{MPP} maximum produced power under standard conditions (STC);
- I_m or I_{MPP} current produced at the maximum power point;
- V_m or V_{MPP} voltage at the maximum power point;
- FF fill factor is a parameter that determines the form of the characteristic curve IV and it is the ratio between the maximum power and the product ($V_{oc} \cdot I_{sc}$) of the open circuit voltage multiplied by the short circuit current.

If a voltage is applied from the outside to the PV cell in reverse direction with respect to standard operation, the generated current remains constant and the power is absorbed by the cell. When a certain value of inverse voltage (“breakdown” voltage) is exceeded, the junction P-N is perforated, as it occurs in a diode, and the current reaches a high value that damage the cell. In absence of light, the generated current is null for reverse voltage values up to the “breakdown” voltage, then there is a discharge current analogously to the lighting conditions (Figure 26– left quadrant).

— Figure 26



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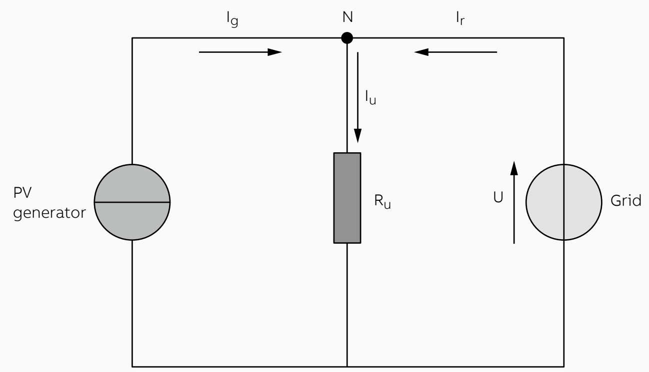
2.3 Grid connection scheme

A PV plant connected to the grid and supplying a consumer plant can be represented in a simplified way by the scheme of Figure 27.
The supply network (assumed to be at infinite short circuit power) is schematized by means of an ideal voltage generator the value of which is independent of the load conditions of the consumer plant.
On the contrary, the PV generator is represented by an ideal current generator (with constant current and equal insolation) whereas the consumer plant is represented by a resistance R_u.

Figure 27



The currents I_g and I_r, which come from the PV generator (I_g) and from the network (I_r) respectively, converge in the node N of Figure 27 and the current I_u absorbed by the consumer plant flows out from the node:

Equation 5

$$I_u = I_g + I_r$$

Since the current on the load is also the ratio between the network voltage U and the load resistance Ru:

Equation 6

$$I_u = \frac{U}{R_u}$$

The relation among the currents becomes:

Equation 7

$$I_r = \frac{U}{R_u} - I_g$$

Considering that during the night hours $I_g = 0$, the current absorbed from the grid results:

Equation 8

$$I_r = \frac{U}{R_u}$$

On the contrary, if all the current generated by the PV plant is absorbed by the consumer plant, the current supplied by the grid shall be null and consequently becomes:

Equation 9

$$I_g = \frac{U}{R_u}$$

When the insolation increases, if the generated current I_g becomes higher than that required by the load I_u, the current I_r becomes negative, that is no more drawn from the grid but put into it.

2

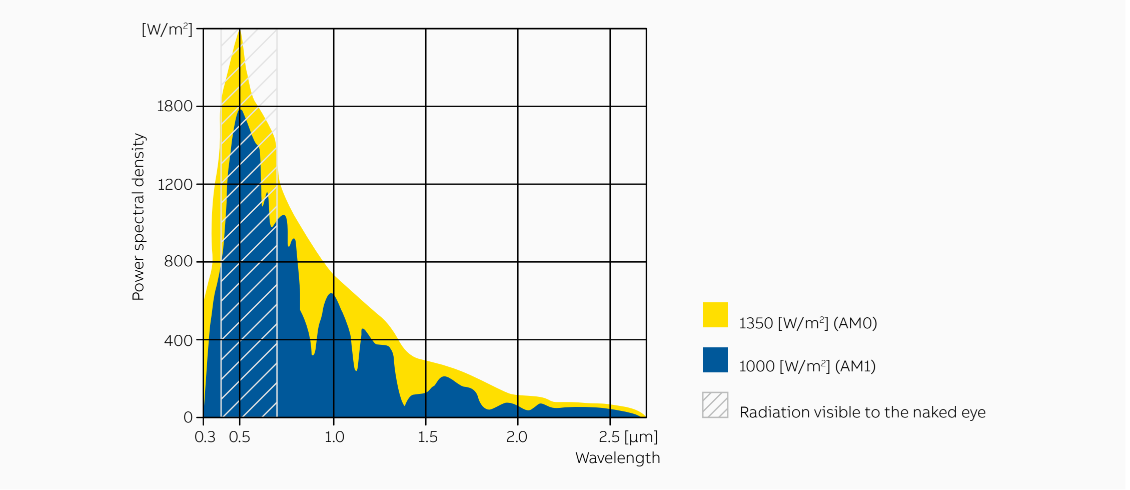
3 The holes in the insolation correspond to the frequencies of solar radiation absorbed by the water vapor present in the atmosphere.

2.4 Nominal peak power

The nominal peak power (kW) is the electric power that a PV plant is able to deliver under standard testing conditions (STC):
- 1 kW/m² insolation perpendicular to the panels;
- 25 °C temperature in the cells;
- air mass (AM) equal to 1.5.

The air mass influences the PV energy production since it represents an index of the trend of the power spectral density of solar radiation. As a matter of fact, the latter has a spectrum with a characteristic W/m²-wavelength which varies also as a function of the air density. In the diagram of Figure 28 the yellow surface represents the radiation perpendicular to the Earth surface, absorbed by the atmosphere, whereas the blue surface represents the solar radiation that really reaches the Earth surface; the difference between the slope of the two curves gives an indication of the spectrum variation due to the air mass[3].

Figure 28



The air mass index AM is calculated as follows:

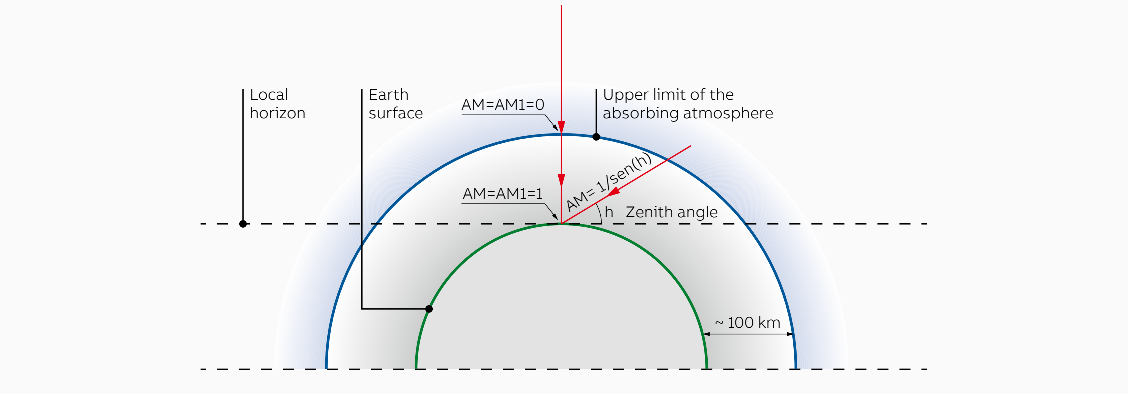
Equation 10

$$AM = \frac{P}{P_0 \cdot sin(h)}$$

where:
P is the atmospheric pressure measured at the point and instant considered [Pa];
P_o is the reference atmospheric pressure at the sea level [$1.013 \cdot 10^5$ Pa];
h is the zenith angle, i.e. the elevation angle of the Sun above the local horizon at the instant considered.

Remarkable values of AM are (Figure 29):
AM = 0 outside the atmosphere where P = 0;
AM = 1 at sea level in a day with clear sky and the sun at the zenith (P = P_o, sen(h) = 1);
AM = 2 at sea level in a beautiful day with the sun at a 30° angle above the horizon (P = P_o, sin(h) =1/2).

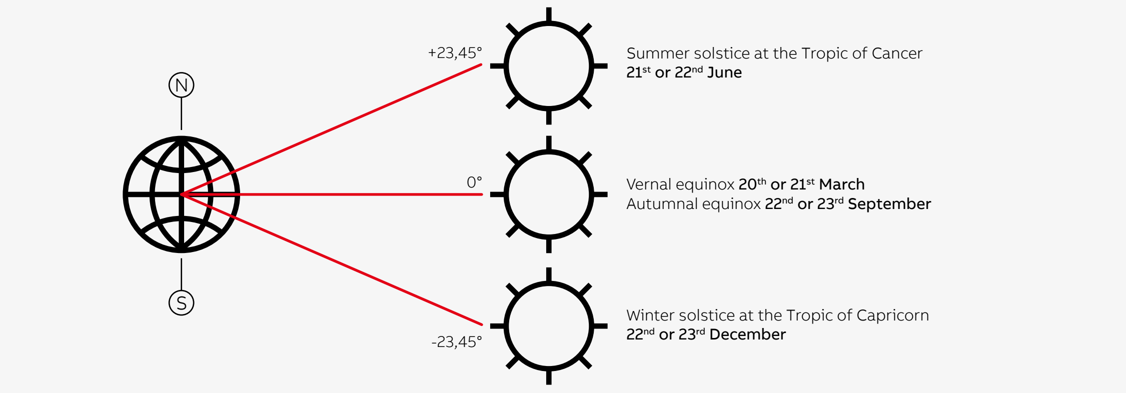
Figure 29



2.5 Inclination and orientation of the modules

The maximum efficiency of a solar panel would be reached if the angle of incidence of solar rays were always 90°. In fact, the incidence of solar radiation varies both according to the latitude as well as to the solar declination during the year. In fact, since the Earth's rotation axis is tilted by about 23.45° with respect to the plane of the Earth orbit about the Sun, at definite latitude the height of the Sun on the horizon varies daily. The Sun is positioned at 90° angle of incidence with respect to the Earth surface (zenith) at the equator in the two days of the equinox and along the tropics at the solstices (Figure 30).

Figure 30



Outside the Tropics latitude, the Sun cannot reach the zenith above the Earth's surface, but it shall be at its highest point (depending on the latitude) with reference to the summer solstice day in the northern hemisphere and in the winter solstice day in the southern hemisphere. Therefore, if we wish to incline the modules so that they can be struck perpendicularly by the solar rays at noon of the longest day of the year, it is necessary to know the maximum height (in degrees) which the Sun reaches above the horizon in that instant, which can be obtained by the following formula:

Equation 11

$$\alpha = 90° - lat + \delta$$

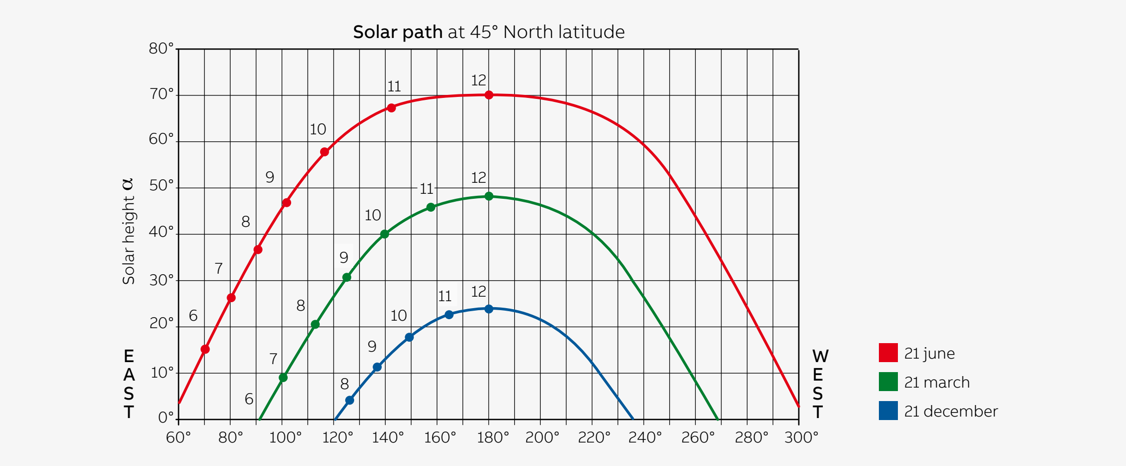
where: lat is the value (in degrees) of latitude of the installation site of the panels;
δ is the angle of solar declination [23.45°]

Finding the complementary angle of α (90°-α), it is possible to obtain the tilt angle β of the modules with respect to the horizontal plane (IEC TS 61836 Solar photovoltaic energy systems - Terms, definitions and symbols) so that the panels are struck perpendicularly by the solar rays in the above-mentioned moment[4]. However, it is not sufficient to know the angle α to determine the optimum orientation of the modules. It is necessary to take into consideration also the Sun path through the sky over the different periods of the year and therefore the tilt angle should be calculated taking into consideration all the days of the year[5] (Figure 31). This allows to obtain a total annual radiation captured by the panels (and therefore the annual energy production) higher than that obtained under the previous irradiance condition perpendicular to the panels during the solstice.

4 On gabled roofs the tilt angle is determined by the inclination of the roof itself.

5 For example, in Italy, the optimum tilted angle is about 30°.

Figure 31



The fixed modules shall be oriented as much as possible to south in the northern hemisphere[6] to get a better insolation of the panel surface at noon local hour and a better global daily insolation of the modules. The orientation of the modules may be indicated with the Azimuth[7] angle (γ) of deviation with respect to the optimum direction to south (for the locations in the northern hemisphere) or to north (for the locations in the southern hemisphere).

Positive values of the Azimuth angles show an orientation to west, whereas negative values show an orientation to east (IEC TS 61836 Solar photovoltaic energy systems - Terms, definitions and symbols).

About ground-mounted modules, the combination of inclination and orientation determines the exposition of the modules themselves (Figure 32)[8]. On the contrary, when the modules are installed on the roofs of buildings, the exposition is determined by the inclination and the orientation of the roof pitches. Good results are obtained through modules oriented to south-east or to south-west with a deviation with respect to the south up to 45° (Figure 33) (for the locations in the northern hemisphere) and to north-east or to north-west with a deviation with respect to the south up to 45° (for the locations in the southern hemisphere). Greater deviations can be compensated by means of a slight enlargement of the modules surface.

—
6 Since the solar irradiance is maximum at noon, the collector surface must be oriented to south as much as possible. On the contrary, in the southern hemisphere, the optimum orientation is obviously to north.

—
7 In astronomy, the Azimuth angle is defined as the angular distance along the horizon, measured from north (0°) to east, of the point of intersection of the vertical circle passing through the object.

—
8 The Figure 32 and Figure 33 are designed for northern hemisphere.

—
Figure 32

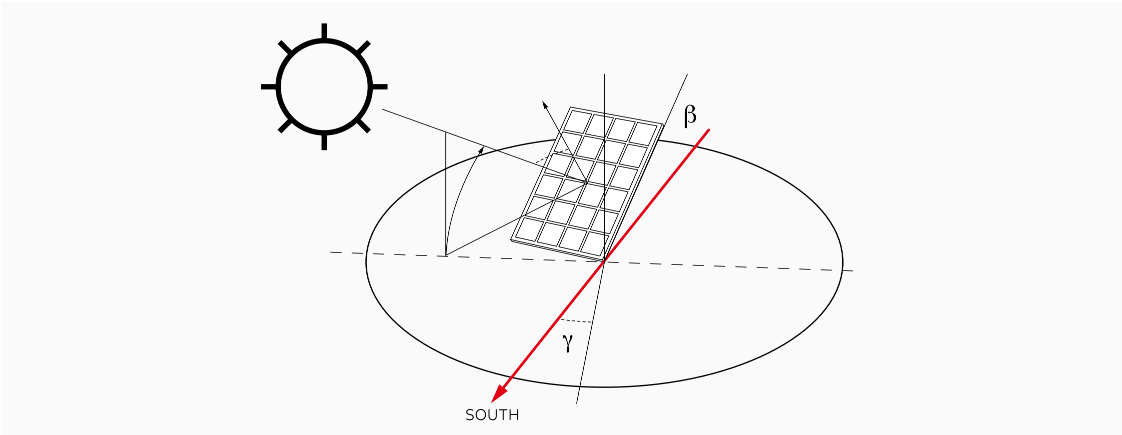


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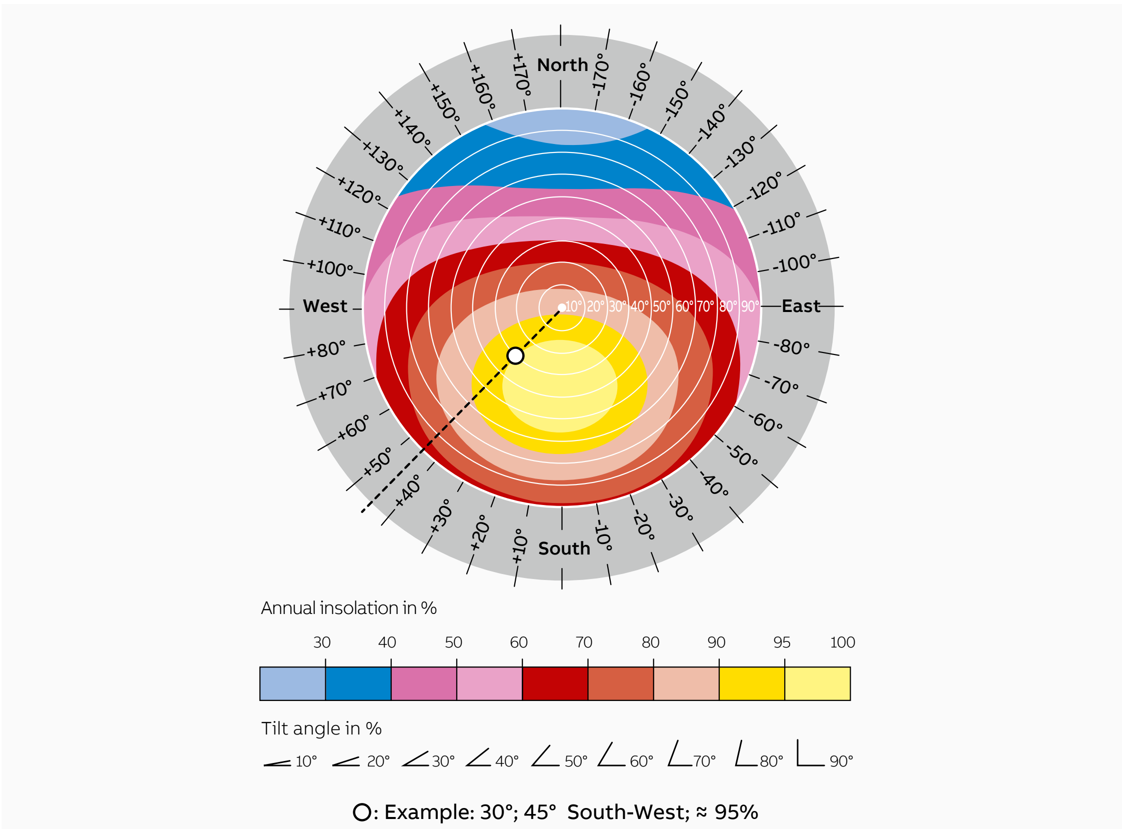
Figure 33



2

2.6 Global Horizontal Irradiation (GHI) & Global Tilted Irradiation (GTI)

The values of the average global solar radiation on the horizontal plane in the place of installation can be collect from:

- National standard: e.g. for Italy the values of the average solar radiation are indicated in the Italian Std. UNI 10349: Heating and cooling of the buildings. Climatic data
- Public databases: eg. For Europe and Africa PVGIS-ESRA databases; for worldwide WRDC databases; for USA NASA-SSE databases.

The annual global solar radiation on the horizontal plane for a given site may vary from a source to the other also by 10%, since it derives from the statistical processing of data gathered over different periods; moreover, these data are subject to the variation of the weather conditions from one year to the other. Consequently, the insolation values have a probabilistic significance, since they represent an expected value, not a definite one.
The global solar radiation data available on the databases are average values on the horizontal plane in a defined timeframe. However, modules and PV systems are generally installed at an inclined angle with regard to the horizontal plane or on tracking systems, in order to maximize the received in-plane irradiance. Therefore, Global solar Irradiation values on the horizontal plane are not representative of the Global Solar Irradiation available at the module surface, and it becomes necessary to estimate the in-plane irradiance.

To estimate the values of the beam and diffuse components on tilted surfaces there are several models in the scientific bibliography which use as input data the irradiation values on the horizontal plane of global and diffuse and/or beam irradiation components. For example, the estimation model implemented in PVGIS is the one developed by Muneer T. (1990) which can be classified as anisotropic of two components; it performs similarly as other more complex models like the anisotropic models of three components like those developed by Perez or Reindl.

A comparison of different models can be found in the scientific paper of Gracia Amillo and Huld (Link).

Considering the complexity of the models, the use of calculation tools is recommendable to obtain the value Global Tilted Irradiation [kWh/m^2].
For European and Africa irradiation dataset, a reference tool is PVGIS-ESRA
http://re.jrc.ec.europa.eu/pvg_tools/en/tools.html#PVP .

For worldwide irradiation dataset, a reference tool is RETScreen
https://www.nrcan.gc.ca/energy/software-tools/7465 or
GLOBAL SOLAR ATLAS https://globalsolaratlas.info/.
For north America and India, a reference tool is PVwatts https://pvwatts.nrel.gov
Using the above tools is possible to obtain directly the Global Tilted Irradiation (GTI) measured in kWh/m^2 per year starting from the Global Horizontal Irradiation (GHI) measured in kWh/m^2 per year.

2

2.7 Predicted energy of a PV system

The predicted energy (IEC TS 61724-1 Photovoltaic system performance – Part 3: Energy evaluation method) is the energy generation of a PV system that is calculated with a specific performance model, using historical weather data that is considered to be representative for the site.
The predicted energy Ep of a PV system the following formula could be applied:

Equation 12

$$E_P = GHI \cdot \Delta_{GPOA} \cdot \eta_{module} \cdot A_{modules} \cdot PR \qquad [kWh]$$

where:
GHI Global Horizontal Irradiation [kWh/m² per year];
Δ_{GPOA} annual gain or loss of irradiance transposition to plane-of array defined by estimation model;
ηmodule initial module conversion efficiency under STC conditions;
Amodules area of the PV modules of the system [m²];
PR Performance ratio, coefficient for losses (range between 0.7 and 0.9, default value = 0.75).
The predicted energy may assume 100 % availability or may be reduced to account for expected times of unavailability (IEC TS 61724-1 Photovoltaic system performance – Part 3: Energy evaluation method).

If the Global Tilted Irradiation (GTI) is already available by calculation tools, the formula is simplified:

Equation 13

$$E_P = GTI \cdot \eta_{module} \cdot A_{modules} \cdot PR \qquad [kWh]$$

where:
GTI Global Tilted Irradiation [kWh/m² per year].

Starting from the above formula, to obtain the predicted energy per year Ep, for each kW, the following formula is applied:

Equation 14

$$E_P = GTI \cdot PR \qquad [kWh/kW]$$

Example 3
We want to determine the annual mean power produced by a 3 kW plant, 30° tilted, installed in Bergamo (Italy). The coefficient for losses is supposed to be equal to 0.75. From the PVGIS-ESRA irradiation dataset a GHI of 1360 kWh/m² and a GTI of 1590 kWh/m² are obtained. The predicted energy annual mean production is equal to:

Equation 15

$$E_P = 3 \cdot 1590 \cdot 0.75 = 3577.5\ [kWh]$$

2.8 Voltages and currents in a PV plant

PV modules usually generate a current from 2 to 10 A, depending from technology and from cells dimensions, and a voltage from 30 to 100V, depending from the number of cells connected in series inside to the module. To get the projected peak power, the modules are electrically connected in series to form the photovoltaic string, which are connected in parallel to form the photovoltaic array[9].
The trend is to develop strings constituted by as many modules as possible, because of the complexity and cost of wiring, in particular of the paralleling switchboards between the strings (photovoltaic string combiner box). The maximum number of modules which can be connected in series (and therefore the highest reachable voltage) to form a string is determined by:
- the components maximum system voltage (e.g. PV Modules, DC connectors, DC cables, etc.);
- the operation range of the inverter;
- the availability of the disconnection and protection devices suitable for the voltage achieved in the photovoltaic combiner box.

For efficiency reasons, the voltage of the inverter is bound to its power: generally, when using inverter with power lower than 10 kW, the voltage range most commonly used is from 250 V to 750 V, whereas if the power of the inverter exceeds 10 kW, the voltage range usually is from 500 V to 1000 V[10].

9 For Terms, definitions and symbols refer to IEC 61836 TS - Solar photovoltaic energy systems - Terms, definitions and symbols

10 High Voltage plant (DC side) > 1000 V is introduced in paragraph 3.2.2.2

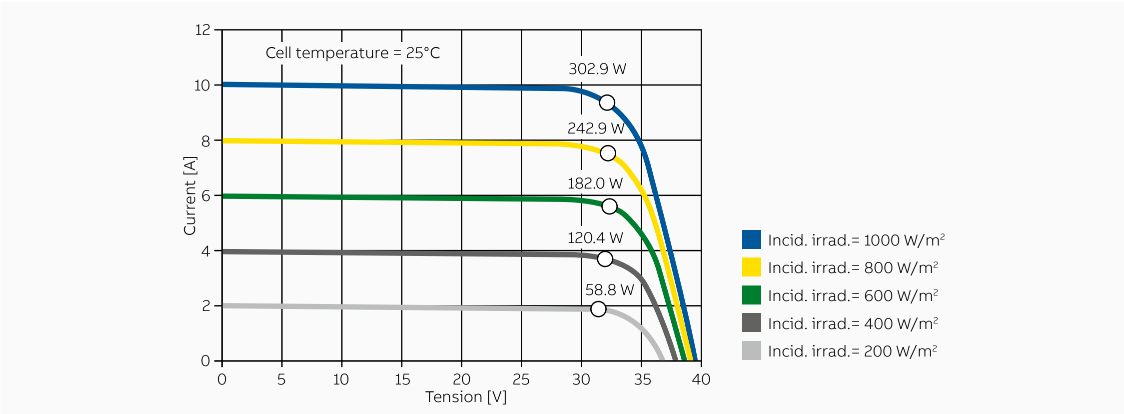
2.9 Variation in the produced energy

The main factors which influence the electric energy produced by a PV installation are:
- irradiance;
- temperature of the modules;
- shading.

2.9.1 Irradiance

As a function of the irradiance incident on the PV module, its characteristic IV curve changes as shown in Figure 34 (characteristic IV curve of a 60 monocrystalline 6-inch cells rated 300W at STC conditions).

Figure 34

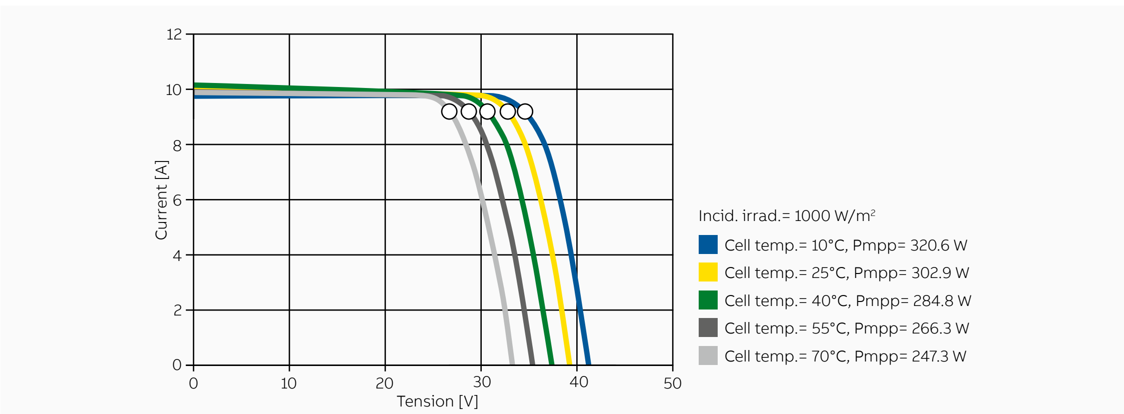


When the irradiance decreases, the generated PV current decreases proportionally, whereas the variation of the open circuit voltage is very small. As a matter of fact, conversion efficiency is not influenced by the variation of the irradiance within the standard operation range of the cells, which means that the conversion efficiency is the same both in a clear as well as in a cloudy day. Therefore, the smaller power generated with a cloudy sky can be referred not to a drop of efficiency, but to a reduced production of current because of lower solar irradiance.

2.9.2 Temperature of the modules

Contrary to the previous case, when the temperature of the PV modules increases, the current produced remains practically unchanged, whereas the voltage decreases and with it there is a reduction in the performances of the PV module in terms of produced electric power as shown in Figure 35 (characteristic IV curve of a 60 monocrystalline 6 inch cells rated 300W at STC conditions).

Figure 35



The variation in the open circuit voltage V_{oc} of a PV module, with respect to PV module open circuit voltage at standard test conditions $V_{oc\ STC}$, as a function of the operating temperature of the cells Tcell, is expressed by the following formula:

Equation 16

$$V_{OC}(T) = V_{OC\ STC} - [\beta' \cdot (25 - T_{cell})]$$

where:

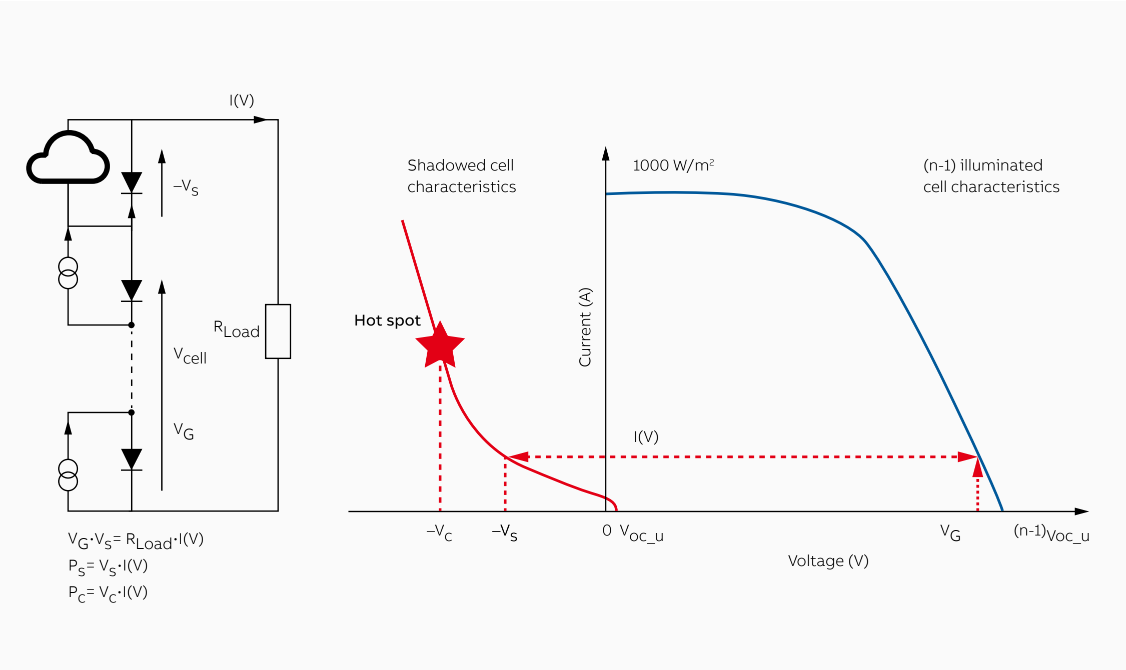
β' is the variation coefficient of the voltage according to temperature and depends on the typology of PV module measured in mV/K (usually -2.2 mV/K/cell for crystalline silicon cell and about -1.5 ÷ -1.8 mV/K/cell for thin film cell);

Therefore, to avoid an excessive reduction in the performances, it is opportune to keep under control the service temperature trying to give the modules good ventilation to limit the temperature variation on them.

2.9.3 Shading

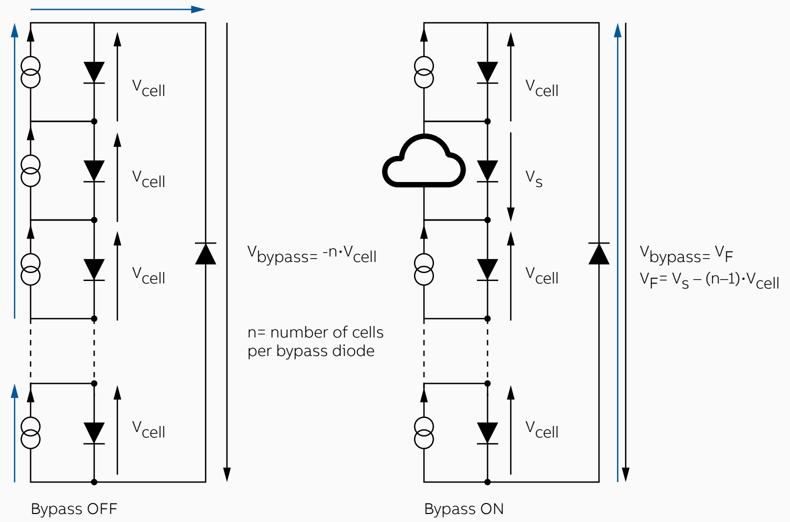
Taking into consideration the area occupied by the modules of a PV plant, part of them (one or more cells) may be shaded by trees, fallen leaves, chimneys, dumps, clouds or by PV modules installed nearby. In case of shading, a PV cell consisting in a junction P-N stops producing energy and becomes a passive load. This cell behaves as a diode which blocks the current produced by the other cells connected in series and thus jeopardizes the whole production of the module.
Besides, the diode is subject to the voltage of the other cells; this may cause the perforation of the junction because of localized overheating (hot spot), and damages to the module (Figure 36).

Figure 36
source Doc ID 019041 Rev 1 ST microelectronics



In order to avoid that one or more shaded cells thwart the production of a whole string, some diodes which by-pass the shaded or damaged part of module are inserted at the module level inside to the Junction Box (JB) that usually is placed at the rear of the PV module. The bypass diode principle is to use a diode in reverse paralleling with several solar cells (Figure 37 see next page). The bypass diode is blocked when all cells are illuminated and it conducts when one or several cells are shadowed.

—
Figure 37
source Doc ID
019041 Rev 1 ST
microelectronics



Thus, functioning of the module is guaranteed but with reduced efficiency. In theory, it would be necessary to insert a by-pass diode in parallel to each single cell, but this would be too onerous for the ratio costs/benefits.
The maximum number of cells to bridge is defined by the breakdown voltage V_c. The literature gives breakdown voltage V_c range for the poly-silicon cells from 12 V to 20 V. For mono-silicon cells the breakdown voltage extends up to 30 V.

For an efficient operation, there are two conditions to fulfil:
- Bypass diode has to conduct when one cell is shadowed (Figure 38);

—
Equation 17

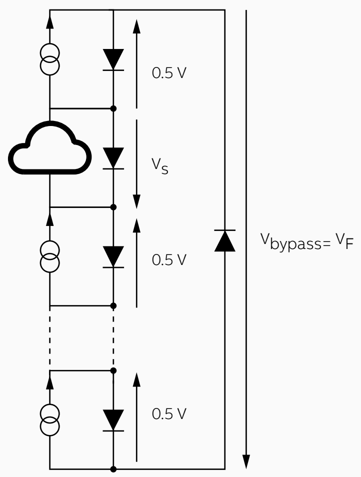
$$V_{bypass} = V_s - V_{OC\ cell} \cdot (n-1)$$

- The shadowed cell voltage Vs must stay under its breakdown voltage V_c. It is defined by the cell manufacturer and is the minimum value of the manufacturing distribution.

—
Equation 18

$$V_S < Vc$$

—
Figure 38
source Doc ID
019041 Rev 1 ST
microelectronics



Considering that:
- $V_{OC\ cell}$ (V_{OC} of a single cell) is around 0.5 V;
- poly-silicon solar cells breakdown voltage V_c is around 12 V;
- bypass diode forward voltage V_F is around 0.5 V,

the maximum number of solar cells (n max) bridged by the bypass diode is 24. This is the common setting used by module manufacturers. Therefore, 2 to 6 by-pass diodes are usually installed for each module depending from the PV module number of cells and interconnection layout.

Installation methods and configurations

Installation methods and configurations

3.1 PV System classification

3.1.1 Scale of system

Photovoltaic systems are generally categorized into four distinct market segments: residential rooftop, commercial rooftop, industrial systems and ground-mount utility-scale systems. Their rated power ranges from a few kilowatts to hundreds of megawatts. A typical residential system is around 1-10 kW and mounted on a sloped roof; commercial systems are around 10-100 kW and are generally installed on low-slope or even flat roofs; industrial systems are around 100-1000 kW and are generally installed on industrial building roofs and/or on the industrial adjacent lot; utility scale systems usually are bigger than 500 kW and are ground mounted and are generally designed in order to fed the generated power into the transmission grid and ensure the highest energy yield for a given investment.

3.1.2 Type of mounting system

The solar array can be either fixed mounted or mounted on a sun tracking system that follows the sun. Two main types of tracking systems are available:
- one axis of rotation: the azimuth of the modules changes during the day according to the sun position.
- two axes of rotation: the azimuth and tilt of the modules change during the day according to the sun position.

the goal of the tracking system is to increase the irradiation on the PV module plane and then the energy generation of PV system.

3.1.3 Mounting system

3.1.3.1 Ground mounted

Ground-mounted PV systems are usually utility-scale photovoltaic plants. The PV array consist of PV modules held in place by racks or frames fixed on the ground with different kind of foundations:
- Earth screw foundation: this type of foundation could be used on soft soils or landfill sites stone-less with a low anchoring depth of 0.8 m;
- Pre-cast concrete blocks: this type of foundation could be used on bedrock areas, lands with little load-bearing capacity, landfill with very shallow anchoring depth, landfill area with stone cover and industrial wasteland with reinforced surface areas;
- Cast-in-place concrete: this type of foundation could be used on bedrock areas, lands with little load-bearing capacity, landfill with very shallow anchoring depth, landfill area with stone cover and industrial wasteland with reinforced surface areas;
- Pile-driving with pre-drilling: this type of foundation could be used on near-surface bedrock zone;
- Pile-driving with concrete collar: this type of foundation could be used on soils with little load-bearing capacity;
- Pile-driving (pole stuck in the ground): this type of foundation could be used on soils that are suitable for pile-driving
- Concrete anchors on concrete surfaces: this type of foundation could be used on concrete-covered and/or conversion areas.

In any case, the measurements and the design of the system depend on the exact and detailed analysis of each specific area in order to determine the load-bearing behaviour regarding the specific wind and snow loads. The structural analysis must be based on regional load values with load assumption and must be in accordance with current national standards (e.g. in Europe in accordance with EN 1990 (Eurocode 0), EN 1991 (Eurocode 1), EN 1993 (Eurocode 3), EN 1999 (Eurocode 9) and further resp. corresponding national standards).

3.1.3.2 Rooftop-mounted

In the last years the installation of rooftop-mounted PV system on the buildings has been making great strides. Basically, three macro-typologies of rooftop-mounted PV system can be mainly defined:

- Integrated PV System: the PV modules replace, either totally or in part, the function of the architectural elements in the buildings, elements as coverings and transparent or semi-transparent surfaces on coverings. The PV modules are designed and realized not only to carry out the function of producing electric power, but also have architectural functions, such as: mechanical rigidity or structural integrity; primary weather impact protection: rain, snow, wind, hail; energy economy, such as shading, daylighting, thermal insulation; fire protection; noise protection; separation between indoor and outdoor environments; security, shelter or safety. This macro-typology can be defined BIPV (Building Integrated PV)[11].
- Partially integrated PV System: the PV modules are applied on buildings and structures for any function and purpose without replacing the building materials of structures themselves. The modules are installed so as to be coplanar to the tangential plane or to the tangential planes of the roof up to a limited height. This macro-typology can be defined BAPV (Building Applied PV)[12].
- Non-integrated PV System: the modules are positioned on the external surfaces of building envelopes, on buildings and structures for any function and purpose. The modules are not coplanar to the tangential plane or to the tangential planes of the roof.

In any case the rooftop mounting system shall be installed applying good engineering practices and respecting the information on the intended use of its components. Those good engineering practices shall be documented and shall hold the documentation by the person(s) responsible at the disposal of the relevant national authorities for inspection purposes for as long as the fixed installation is in operation. The measurements and the design of the system depend on the exact and detailed analysis of each specific area in order to determine the load-bearing behaviour regarding the specific wind and snow loads. The structural analysis must be based on regional load values with load assumption and must be in accordance with current national standards (e.g. in Europe in accordance with EN 1990 (Eurocode 0), EN 1991 (Eurocode 1), EN 1993 (Eurocode 3), EN 1999 (Eurocode 9) and further resp. corresponding national standards). Guidance on the principles and requirements of structural design for the safety and serviceability of the structural connection between solar energy panels that are mounted on flat or pitched roofs are provided by the European Technical report CEN/TR 16999 Solar energy systems for roofs - Requirements for structural connections to solar panels.

3.1.3.3 Carport

In order to use the existing surfaces for the installation of PV modules, carport is a good way to use areas for solar energy while also providing shade for parking or pedestrian areas. The foundations of the carports are available in cast-in-place concrete ballasts, concrete pillars, and micropile integrations. Also for this kind of installation the measurements and the design of the system depend on the exact and detailed analysis of each specific area in order to determine the load-bearing behaviour regarding the specific wind and snow loads: the structural analysis must be based on regional load values with load assumption and must be in accordance with current national standards (e.g. in Europe in accordance with EN 1990 (Eurocode 0), EN 1991 (Eurocode 1), EN 1993 (Eurocode 3), EN 1999 (Eurocode 9) and further resp. corresponding national standards). Moreover, special local requirements for park area restriction and safety condition must be considered during the design of the PV system.

3.1.3.4 Other architectural integration

Thanks to the technical development of the photovoltaic industry, PV system can easily be architectonically integrated into building construction elements such as vertical façade components, both with opaque or transparent surfaces. Furthermore, PV construction facades elements could also be provided by openings like doors or windows.

—
11 Reference about the BIPV are:
- European standard EN 50583-1 Photovoltaics in buildings - Part 1: BIPV modules;
- European standard EN 50583-2 Photovoltaics in buildings - Part 2: BIPV systems;
- International standard ISO/TS 18178 Glass in building - Laminated solar photovoltaic glass for use in buildings;
- Project of international standard draft IEC 63092-1 ED1 Photovoltaics in buildings – Part 1: Building integrated photovoltaic modules;
- Project of international standard draft IEC 63092-2 ED1 Photovoltaics in buildings – Part 2: Building integrated photovoltaic systems;
- Korean Standard (KS) C 8577 Building integrated photovoltaics (BIPV) Modules;
- Spanish Technical Building Code

—
12 BAPV (Building Applied PV): Photovoltaic modules are considered to be building-attached, if the PV modules are mounted on a building envelope and do not fulfil the criteria for building integration. The integrity of the building functionality is independent of the existence of a building attached photovoltaic module.

3.2 PV plant layout

3.2.1 Type of installation

As already introduced in paragraph 1.2.1, the PV modules strings, that compose the photovoltaic generator, could be connected to one or more inverters depending from the type of installation and then a different kind of distribution is obtained.

3.2.1.1 Decentralized distribution

Decentralized distribution is usually adopted in the PV plants where the photovoltaic generator is subject to different irradiation conditions (e.g. different tilt orientation of the PV modules; different azimuth orientation of the PV modules; part of the PV generator shadowed; etc.). using multiple inverters, Multiple MPPT inputs are available and then the different parts of the PV files subject to different irradiation condition could be connected to different MPPT.
Moreover, generally the conversion efficiency of string inverters is higher that the centralized inverter. Nowadays several string inverters have the fuses and DC switch included, so the DC combiner boxes are not required in the PV installation. The use of string inverter implies that the AC outputs of the inverters are combined in the AC combiner boxes as shown on Figure 8. The AC combiner boxes usually contain fuse holders, SPDs and MCCBs. Decentralized distribution offers a very interesting pro: in case of inverter fault, only a portion of the PV generator is out of service and then the power production is not completely compromised and the uptime is maximized. Lastly the decentralized distribution offers a simple fault finding.

3.2.1.2 Centralized distribution

The centralized distribution is usually adopted in the large-size PV plants, where the photovoltaic generator is uniformly orientated. In the centralized distribution the PV modules strings, that compose the photovoltaic generator, are connected in parallel mode in the combiner boxes. The parallel of multiple combiner boxes is connected to the recombiner box and then to the central inverter.
The power distribution is achieved with DC cables. DC power distribution is more efficient and cheaper than AC because:

- there are two conductors used in DC transmission while three conductors required in AC transmission;
- considering the Voltage level generated by PV, the DC cables have smaller cross section than AC cables (considering equal power level);
- there are no Inductance and Surges (High Voltage waves for very short time) in DC transmission; due to absence of inductance, there are very low voltage drop in DC transmission lines comparing with AC;
- in DC Supply System, the sheath losses in underground cables are low.

According to this scenario low installation costs and low energy lost are the main pros of centralized distribution.

3.2.2 PV system design

The international standards available that indicates requirements for the design of PV arrays, DC wiring and electrical protections devices are listed here below:

- IEC 62548:2016 Photovoltaic (PV) arrays - Design requirements
- IEC TS 62738:2018 Ground-mounted photovoltaic power plants - Design guidelines and recommendations
- IEC 62817:2014 Photovoltaic systems - Design qualification of solar trackers
- NFPA 70: National Electrical Code Article 690, “Solar Photovoltaic (PV) Systems when the NEC first adopted Article 690.
- IEC 62446-1:2016 Photovoltaic (PV) systems - Requirements for testing, documentation and maintenance - Part 1: Grid connected systems - Documentation, commissioning tests and inspection

The design, erection and verification of the PV system shall be in compliance with the requirements of IEC 60364 all parts (Low-voltage electrical installations).

3.2.2.1 String and central inverters configurations

Inverter size selection
The selection of the inverter and of its sizing is carried out according to the PV generator rated power. Starting from the PV generator rated power ($P_{DC\ PV\ GEN}$), according to the distribution of the annual solar irradiation in the installation site and according to the installation conditions, the designer shall take the decision if inverter should be oversized ($P_{DC\ Max\ Inverter} > P_{DC\ PV\ GEN}$) or undersized ($P_{DC\ Max\ Inverter} < P_{DC\ PV\ GEN}$). In case of undersized inverter, when the generated power will be higher than that usually estimated, the inverter will automatically limit the power output.
The maximum DC power rate of the inverter ($P_{DC\ Max\ Inverter}$), according to the inverter efficiency, define maximum AC power rate of the inverter.
The inverter efficiency is influenced by the % of rated Output Power and by the PV array voltage.

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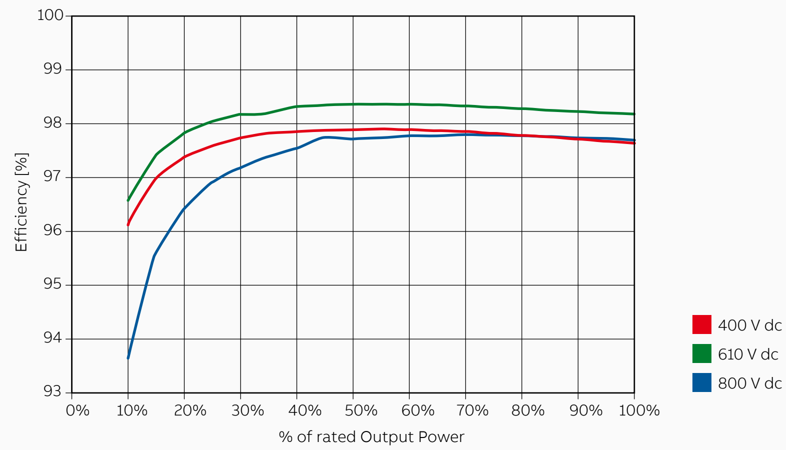
Figure 39
Efficiency curves of TRIO 50



Determining the PV module max V_{oc} (according to IEC 60364-7-712).
As already introduced in the paragraph 2.9.2 the variation of open circuit voltage V_{oc} of a PV module is a function of the operating temperature of the cells. The open circuit voltage V_{oc} is inversely proportional to the cell temperature and then it is highest at lower cell temperature. The maximum open circuit voltage $V_{oc\ MAX}$ can be calculated using the following data:
- lowest temperature that can be expected at the PV installation location;
- PV module open circuit voltage at STC condition $V_{oc\ STC}$;
- PV module temperature coefficient.

The formulas to calculate $V_{oc\ MAX}$ are:

—
Equation 19

$$V_{OC\ MAX} = V_{OC\ STC} \cdot \left[1 + \left({}^{\beta}/_{100}\right) \cdot (T_{min} - 25)\right]$$

or

—
Equation 20

$$V_{OC\ MAX} = V_{OC\ STC} + \beta' \cdot (T_{min} - 25)$$

where:
T_{min} is assumed equal to the lowest temperature that can be expected at the PV installation location;
$V_{OC\ STC}$ is the PV module open circuit voltage at standard test conditions;
β is the variation coefficient of the voltage according to temperature and depends on the typology of PV module; it is measured in [%/K];
β’ is the variation coefficient of the voltage according to temperature and depends on the typology of PV module; it is measured in [mV/K].
For some kind of PV modules, electrical characteristics, during the first weeks of operation, are higher than the characteristics indicated in the name plate of the PV module: this phenomenon shall be considered in the calculation of $V_{OC\ MAX}$. Furthermore, the electrical characteristics of other type of PV modules fall down during the life time of the PV modules for degradation mechanism (LID, LETID, PID): this phenomenon shall be considered in the calculation of $V_{OC\ MAX}$.

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3

Example 4
We would like to estimate the maximum open circuit voltage ($V_{oc\ MAX}$) of a 60 monocrystalline 6” cells rated 300 W at STC conditions in Berlin (Germany). The minimum ambient temperature in Berlin (Germany) is -8 °C. The voltage temperature coefficient (β) of the above PV module is -0,29 [%/K]. The open circuit voltage of the above module ($V_{OC\ STC}$) is 39.4 V.

— Equation 21

$$V_{OC\ MAX} = 39.4 \cdot [1 + (-0.29\%) \cdot ((-8) - 25)] = 39.4 \cdot [1 - 0.0029 \cdot (-8 - 25)]$$
$$V_{OC\ MAX} = 39.4 \cdot [1 + 0.0029 \cdot 33] = 43.17\ V$$

Determining the PV module min V_{MPP}
On the basis of the above, the minimum MPP voltage $V_{MPP\ min}$ can be calculated using the following data:
- maximum temperature that can be expected at the PV installation location;
- PV module MPP voltage at STC condition $V_{MPP\ STC}$;
- PV module temperature coefficient.

The temperatures of the solar cells depend on the selected mounting system and on the ambient temperature. For tilt angle ground mounted installation ΔT between ambient e cell temperature is +30°C; for solar tracker installation ΔT between ambient e cell temperature is +25°C; for roof top installation (PV modules coplanar to the roof surface) ΔT between ambient e cell temperature is +35°C. The formulas to calculate $V_{MPP\ min}$ are:

— Equation 22

$$V_{MPP\ min} = V_{MPP\ STC} \cdot [1 + \beta \cdot (T_{cell} - 25)]$$

or

— Equation 23

$$V_{MPP\ min} = V_{MPP\ STC} + \beta' \cdot (T_{cell} - 25)$$

where:
T_{cell} is the maximum cell temperature that can be expected at the PV installation location
$V_{MPP\ STC}$ is the PV module MPP voltage at standard test conditions;
β is the variation coefficient of the voltage according to temperature and depends on the typology of PV module; it is measured in [%/K];
β’ is the variation coefficient of the voltage according to temperature and depends on the typology of PV module; it is measured in [mV/K].

Example 5
We would like to estimate the minimum MPP voltage ($V_{MPP\ min}$) of a 60 monocrystalline 6” cells rated 300 W at STC conditions in Berlin (Germany). The maximum ambient temperature in Berlin (Germany) is 23°C. The voltage temperature coefficient (β) of the above PV module is -0.29 [%/K]. The MPP voltage at STC condition of the above module ($V_{MPP\ STC}$) is 31.2 V.
The modules are installed on the roof and are coplanar to the roof surface.

— Equation 24

$$T_{cell} = T_{ambient} + 35 = 23 + 35 = 58$$

— Equation 25

$$V_{MPP\ min} = 31.2 \cdot [1 + (-0.29\%) \cdot (58 - 25)] = 31.2 \cdot [1 - 0.0029 \cdot (33)]$$
$$V_{MPP\ min} = 31.2 \cdot [1 - 0.0029 \cdot 33] = 28.21\ V$$

Determining the Maximum Number of PV Modules per String
The maximum number of PV modules connected in series that could be connected to the inverter is defined based on the assumption that the string voltage is always below the maximum input voltage of the inverter. In case string voltage exceeds the input voltage of the inverter, damage to the inverter could occur by overvoltage.

— Equation 26

$$N_{MAX\ Module} \le \frac{V_{MAX\ Inverter}}{V_{OC\ MAX\ Module}}$$

where:
$N_{MAX\ Module}$ is the maximum number of PV modules connected in series per string;
$V_{MAX\ Inverter}$ is the maximum input voltage of inverter;
$V_{OC\ MAX\ Module}$ is the PV module maximum V_{oc}.

The maximum system voltage of all the components of the PV system (combiner boxes, switch, connectors, cables, PV Modules, etc.) must exceed the maximum string voltage.

—
Equation 27

$$V_{MAX\ system} \geq N_{MAX\ Module} \cdot V_{OC\ MAX\ Module}$$

where:
- $V_{MAX\ system}$ is the maximum system voltage of all components of the PV system;

Example 6
We would like to estimate the maximum number of modules (60 monocrystalline 6" cells rated 300 W at STC) connected in series per string in the above installation in Berlin (Germany).
In Example 4 the PV module maximum V_{oc} was calculated and it is $V_{OC\ MAX\ Module}$ = 43.17 V.
The maximum input voltage of inverter is 1000 V.

—
Equation 28

$$N_{MAX\ Module} \leq \frac{1000}{47.17} = 21.19$$

The maximum number of modules that could be connected in series to be connected to the inverter are 21.

Determining the PV string max V_{oc}
The maximum open circuit voltage of the string ($V_{OC\ MAX\ String}$) at the lowest temperature that can be expected at the PV installation location could be calculated as follow:

—
Equation 29

$$V_{OC\ MAX\ String} = N_{MAX\ Module} \cdot V_{OC\ MAX\ Module}$$

where:
$N_{MAX\ Module}$ is the maximum number of PV modules connected in series per string;
$V_{OC\ MAX\ Module}$ is the PV module maximum V_{oc}.

Determining the Minimum Number of PV Modules per String
In case the string voltage falls below the minimum MPP voltage of the inverter, MPP tracking is not possible or yield losses can occur. The minimum number of PV modules connected in series that could be connected to the inverter is defined based on the assumption that the string voltage at MPP condition is always above the minimum MPP voltage of the inverter.

—
Equation 30

$$N_{\min mod} \geq \frac{V_{\min MPPT\ Inverter}}{V_{MPP\ \min Module}}$$

where:
$N_{min\ Module}$ is the minimum number of PV modules connected in series per string;
$V_{min\ MPPT\ Inverter}$ is the minimum MPP voltage of the inverter;
$V_{MPP\ min\ Module}$ is the PV module minimum V_{MPP}.

Example 7
We would like to estimate the minimum number of modules (60 monocrystalline 6" cells rated 300 W at STC) connected in series per string in the above installation in Berlin (Germany). In Example 5 the PV module minimum V_{MPP} was calculated and it is $V_{MPP\ min\ Module}$ = 28.21 V. The minimum MPP voltage of the inverter is 450 V.

—
Equation 31

$$N_{\min Module} \geq \frac{450}{28.21} = 15.95$$

The minimum number of modules that could be connected in series (to assure that the string voltage at MPP condition is always above the minimum MPP voltage of the inverter) is 16.

Number of PV Modules per String
The number of PV modules per string must:
- not exceed the Maximum Number of PV Modules per String;
- not be less than Minimum Number of PV Modules per String.

3

Determining the Maximum PV Module Current

As already introduced in the paragraph 2.9.2 the variation of short-circuit current I_{sc} of a PV module is a function of the operating temperature of the cells. The short-circuit current I_{sc} is proportional to the cell temperature and then it is highest at maximum cell temperature. On the basis of the above, the maximum PV module short-circuit current $I_{sc\ MAX\ Module}$ can be calculated using the following data:

- maximum temperature that can be expected at the PV installation location;
- PV module short-circuit current at STC condition $I_{sc\ STC}$;
- PV module temperature coefficient.

The temperatures of the solar cells depend on the selected mounting system and on the ambient temperature.

For tilt angle ground mounted installation ΔT between ambient e cell temperature is +30°C; for solar tracker installation ΔT between ambient e cell temperature is +25°C; for roof top installation (PV modules coplanar to the roof surface) ΔT between ambient e cell temperature is +35°C.

The formulas to calculate $I_{SC\ MAX}$ are:

— Equation 32

$$I_{SC\ MAX\ Module} = I_{SC\ STC} \cdot [1 - \alpha \cdot (25 - T_{cell})]$$

or

— Equation 33

$$I_{SC\ MAX\ Module} = I_{SC\ STC} - \alpha' \cdot (25 - T_{cell})$$

where:

T_{cell} is the lowest temperature that can be expected at the PV installation location

$I_{SC\ STC}$ is the PV module short-circuit current at standard test conditions;

α is the variation coefficient of the current according to temperature and depends on the typology of PV module; it is measured in [%/K];

α’ is the variation coefficient of the current according to temperature and depends on the typology of PV module; it is measured in [mA/K].

Furthermore, the IEC 60364-7-712 propose a simplified formula:

— Equation 34

$$I_{SC\ MAX\ Module} = K \cdot I_{SC\ STC}$$

where:

K is a correction factor and its minimum value is 1.25; it shall be increased to take into account environmental situations.

Example 8

We would like to estimate the maximum short-circuit current ($I_{SC\ MAX\ Module}$) of a 60 monocrystalline 6” cells rated 300 W at STC conditions in Berlin (Germany). The maximum ambient temperature in Berlin (Germany) is 23°C. The current temperature coefficient (α) of the above PV module is +0.05 [%/K]. The short-circuit current at STC condition of the above module ($V_{MPP\ STC}$) is 9.87 A.

The modules are installed on the roof and are coplanar to the roof surface.

— Equation 35

$$T_{cell} = T_{ambient} + 35 = 23 + 35 = 58$$

— Equation 36

$$I_{SC\ MAX\ Module} = 9.87 \cdot [1 - (0.05\%) \cdot (25 - 58)] = 9.87 \cdot [1 + 0.0005 \cdot 33] = 10.03\ A$$

Determining the Maximum PV string Current

As already introduced in the paragraph 1.2.1, in a series connection of modules the current does not add up; the total current in a string of PV modules connected in series is equal to the current generated by the single module. On the basis of the above, the maximum string short-circuit current $I_{sc\ MAX\ string}$ is equal to the maximum PV module short-circuit current $I_{sc\ MAX\ module}$.

—
Equation 37

$$I_{SC\ MAX\ Module} = I_{SC\ MAX\ string}$$

Determining the String Number

Assuming that a correct inverter sizing was carried out according to the PV generator rated power, as soon as the number of modules per string is defined, the number of strings per inverter must be verified.

In case of **string inverters with independent MPPT**, the maximum number of strings connected in parallel that could be connected to the single DC input channel of the inverter is defined based on the assumption that the maximum string short-circuit current $I_{sc\ MAX\ string}$ is always below the maximum input current of the single DC input channel of the inverter.

—
Equation 38

$$N_{MAX\ string} \leq \frac{I_{Max\ input}}{I_{SC\ MAX\ string}}$$

In case of **string inverters or a central inverter with a single MPPT**, the maximum number of strings connected in parallel that could be connected to inverter is defined based on the assumption that the maximum string short-circuit current $I_{sc\ MAX\ string}$ is always below the maximum input current of inverter.

—
Equation 39

$$N_{MAX\ string} \leq \frac{I_{Max\ inverter}}{I_{SC\ MAX\ string}}$$

In case of **central inverter**, the determination of string number must be performed also for the combiner box.

In any case the max current level of the components used in the combiner boxes (connectors, switch, fuses) and the inverter must be suitable for the number of strings connected.

Example 9

We would like to estimate the maximum number of strings that could be connected to the single DC input channel of a 20 kW string inverters with 2 independent MPPT in Berlin (Germany). Each string is composed from 18 modules (60 monocrystalline 6” cells rated 300 W at STC). The maximum input current for each single DC input channel of the inverter is 25 A. The maximum input current of the inverter is totally 50 A. In Example 8 the maximum short-circuit current ($I_{SC\ MAX\ Module}$) of a 60 monocrystalline 6” cells rated 300 W at STC conditions in Berlin (Germany) was calculated and it is $I_{SC\ MAX\ Module}$ = 10.03 A. The maximum string short-circuit current $I_{sc\ MAX}$ string is equal to the maximum PV module short-circuit current $I_{sc\ MAX\ module}$ and then $I_{sc\ MAX\ string}$ = 10.03 A.

—
Equation 40

$$N_{MAX\ string\ per\ input} \leq \frac{25}{10.03}$$

—
Equation 41

$$N_{MAX\ string\ per\ inverter} \leq \frac{50}{10.03}$$

The maximum number of strings that could be connected to the single DC input channel of a 20 kW string inverters with 2 independent MPPT in Berlin (Germany) is 2 and the maximum number of strings that could be connected to the inverter is 4.

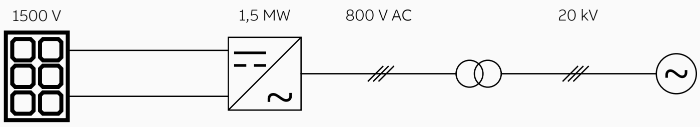
3

3.2.2.2 Higher Voltage Photovoltaic plants

Due to the falling PV module prices, nowadays the BOS costs are of greater significance. In order to make PV electricity production cheaper, the goal is to reduce the Balance of System (BOS) costs. This goal could be achieved using bigger inverter stations and higher system voltage. Due to the higher voltages, it is possible to transfer more power with the same wire cross-sections. Moreover, a power plant with higher voltage require also a reduction of the number of combiner boxes. The upper limit for higher system voltage will be the low voltage standards which goes up to 1500 V DC and 1000 V AC.

3

—
Figure 40
high voltage
PV plant scheme



The state of the art of the maximum system voltage of PV modules available on the market is 1500 V. This value of rated voltage could introduce some issues related to the PV modules performance degradation (e.g. PID): in order to avoid these issues, according to the PV modules producer recommendations, some solutions shall be considered (e.g. functional earth, etc.).
Nowadays inverters with 800 V AC outputs are used; also string inverters with 800 V AC outputs are used and then more AC power combining is required before the 800 V AC transformer.

3.3 Grid Connection

PV plants could be connected to LV, MV or HV grid depending on their rated power (e.g. Residential [1-10 kW] – LV; Commercial and industrial [10-1000 kW] - LV or MV; Utility scale [> 500 kW] - MV or HV).
The connection of PV system (active users) to Utilities grid is subject to the grid code requirements[13].
The PV system shall be disconnected from the grid whenever the voltage and frequency values of the grid itself are out of the ranges prescribed by the grid code.
Such disconnection is usually carried out by an Interface Device that trips after receiving an opening command sent by an external Interface Protection System (relay).
The grid code establish if the PV plant shall be connected to the LV or to the MV grid according to the rated power of the PV Plant; according to the PV plant connection type the interface protection system is able to monitor voltage and frequency values on the related grid.

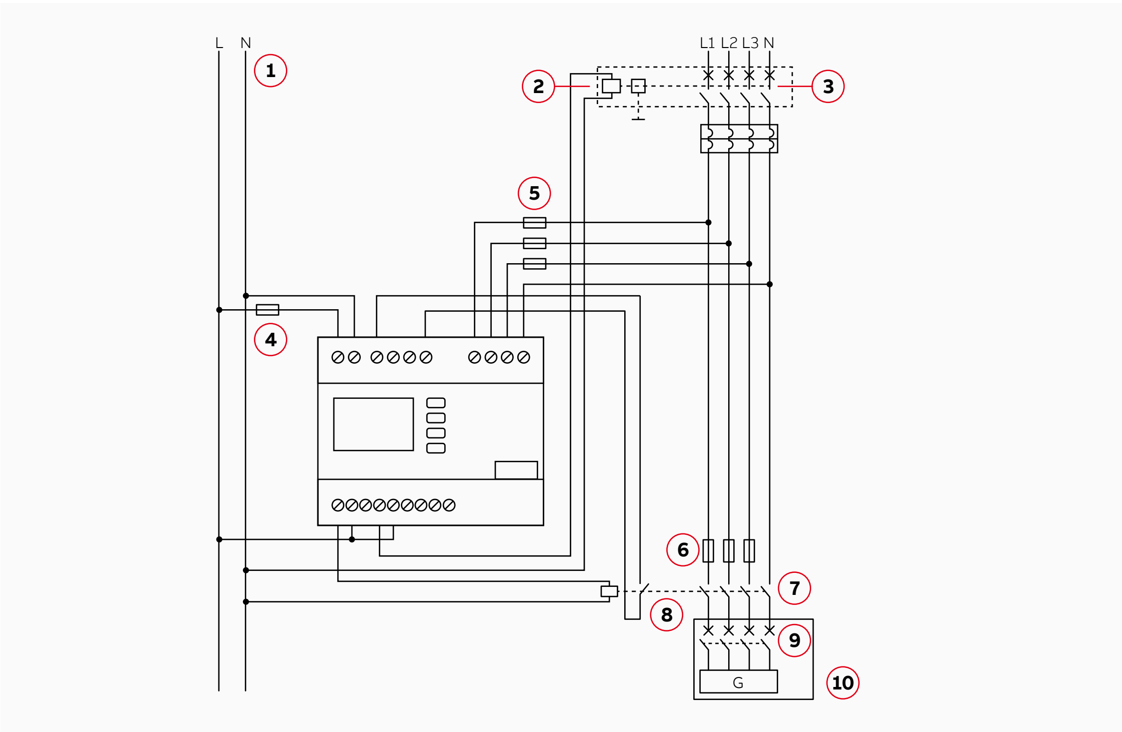
13 The Characteristics of the utility interface for Photovoltaic (PV) systems are included in the standard IEC 61727:2004. This standard describes specific recommendations for systems rated at 10 kVA or less, such as may be utilized on individual residences single or three phase. This standard applies to interconnection with the low-voltage utility distribution system. In any case the grid codes released by each country supersede this standard.

14 The connection to the grid is regulated by the national grid code.

3.3.1 LV interface protection system

The small residential and commercial PV plants usually[14] are connected to LV grid.
If all phases are present with voltage and frequency values within their permissible range, the IPS output relay energizes after the adjustable start-up and consequently PV system is connected to the grid.
If one or more phases are not present or if the voltage and frequency values are not within their permissible range, the IPS output relay de-energizes and consequently the PV system is disconnected from the grid.

Figure 41
e.g. of connection of Interface Protection System (IPS) to the Interface Protection Device (ID) in LV PV systems.



Legend

1 Control supply voltage for the IPS and the trip device coil
2 Shunt trip coil for feedback function. This coil can control GD General device
3 Main circuit-breaker GD
4 Protection fuse for the IPS
5 Protection fuse for measuring circuit of the IPS
6 Interface protection device (ID) short-circuit protection
7 ID: Automatic circuit-breaker or contactor equipped with low voltage coil and motor for automatic closure
8 IPS auxiliary contact for feedback function
9 Generator/inverter circuit-breaker (GenD)
10 Generator and/or inverter

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3.3.2 MV interface protection system

When a PV system is connected to MV grid, the Interface Protection System (IPS) is a little bit more complex because the protection system is the ensemble of:

- the voltage transformers (VTs)
- the relays with adequate settings.

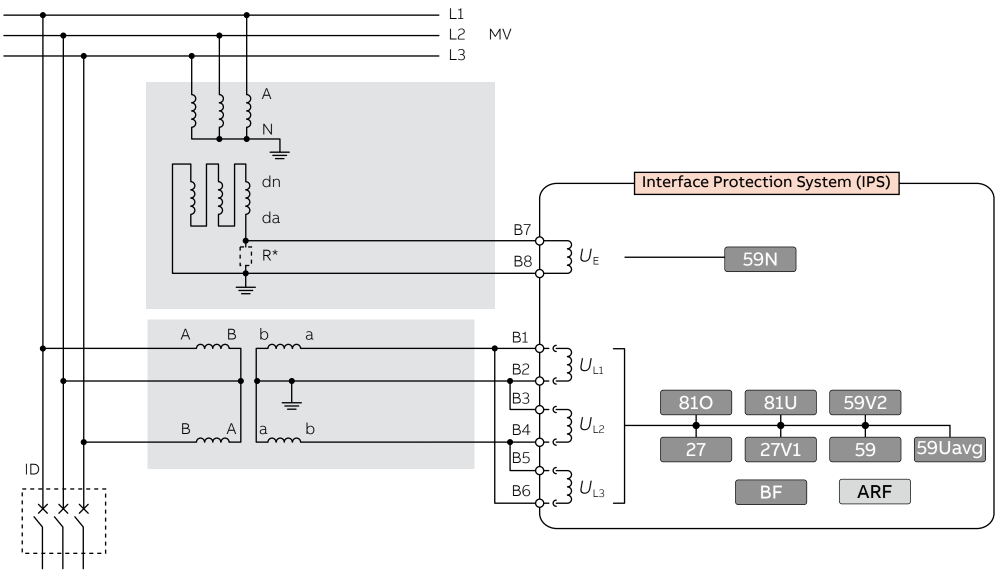
The Interface Protection System (IPS) usually[15] is set with the following protections:

- undervoltage protections;
- under/over and rate of change of frequency
- overcurrent (directional and non-directional)[16].

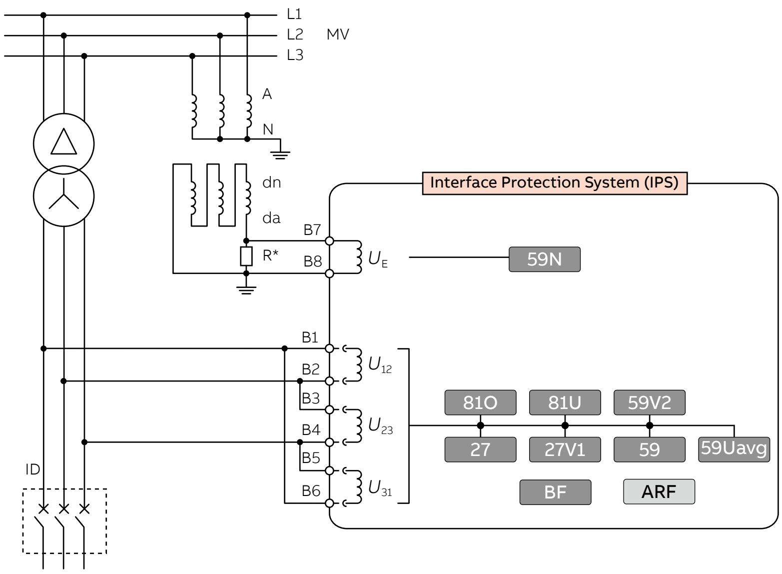
In the PV system connected to the MV grid, according to the electric configuration, the IPS relay can control an Interface Protection Device – ID (e.g. a circuit-breaker) that operate in LV or in MV.

—
15
The protection required are defined by the national grid code.
—
16
This protection is usually implemented in the General protection.

—
Figure 42
e.g. Voltage inputs - “V” connections VTs and residual voltage acquired with open delta VT



* Antiferrorisonance



—
Figure 43
e.g. Direct measure of LV phase-to-phase voltages and residual voltage acquired with open delta VT in MV

Often the grid codes establish that the DSOs (Distribution system operators) shall be able to disconnect the PV system from the grid in order to safe operation of the grid. For this reason a GSM modem, able to receive command from the DSO, is connected to the Interface protection System; according to the DSO commands the modem is able to energize or de- energize the output relay of the Interface protection System and then connect or disconnect the PV system from the grid.

3

3.4 Choice of cables

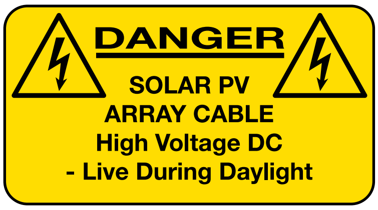
3.4.1 Types of cables and installation conditions

The cables used for wiring the DC section of a grid-connected PV system need to be selected to withstand the challenging conditions of sunlight (ultra-violet light), extreme heat, freezing conditions (cables routed behind a PV array must be rated for a temperature range of at least of -15°C to 90°C), regular contact with rainwater, current and voltage (DC voltage up to 1,5 kV between conductors and between conductor and earth) operation conditions.
IEC developed a standard to test the solar cable: IEC 62930 “Electric cables for photovoltaic systems with a voltage rating of 1,5 kV DC”. This standard includes halogen free low smoke cables and cables that can contain halogens.
A similar standard, EN 50618 “Electric cables for photovoltaic systems”, was published in Europe: it restricted the cable to halogen free materials. The coding of solar cables in Europe is H1Z2Z2-K.
Also, UL standard was developed for the PV wires: UL 4703 “Standard for Photovoltaic Wire”.
According to the installation region, the solar cables must be approved according to the above suitable standards.
IEC 60364-7-712 “Low voltage electrical installations - Part 7-712: Requirements for special installations or locations - Solar photovoltaic (PV) power supply systems” require that cables on the DC side shall be selected and erected so as to minimize the risk of earth faults and short-circuits.
Usually PV strings cables are double or reinforced insulation as their means of shock protection; to maintain this feature they must not:

- be buried in walls or in the metal frames of the fixing systems;
- bent to a radius less than 8 times the overall cable diameter (NEC Section 300.34 radius requirements).

Often the PV strings cables are mounted immediately behind the array and are subject to thermal and wind movement of arrays/modules. Cables mechanical damage may lead to increase instances of shock and fire risk.
PV cables are commonly black in colour to assist in UV resistance and exterior cable colour coding is not required for PV systems: by the way it is recommendable to use black wires for negative side of PV strings cables and red ones for positive side of PV strings cables.
Where long PV strings cables run are necessary, it is recommendable to fix labels along the DC cables. Danger labels fixed every 5 to 10 m is considered enough to identify the cables on straight runs where a clear view is possible between labels.

—
Figure 44
Danger label for array PV cables



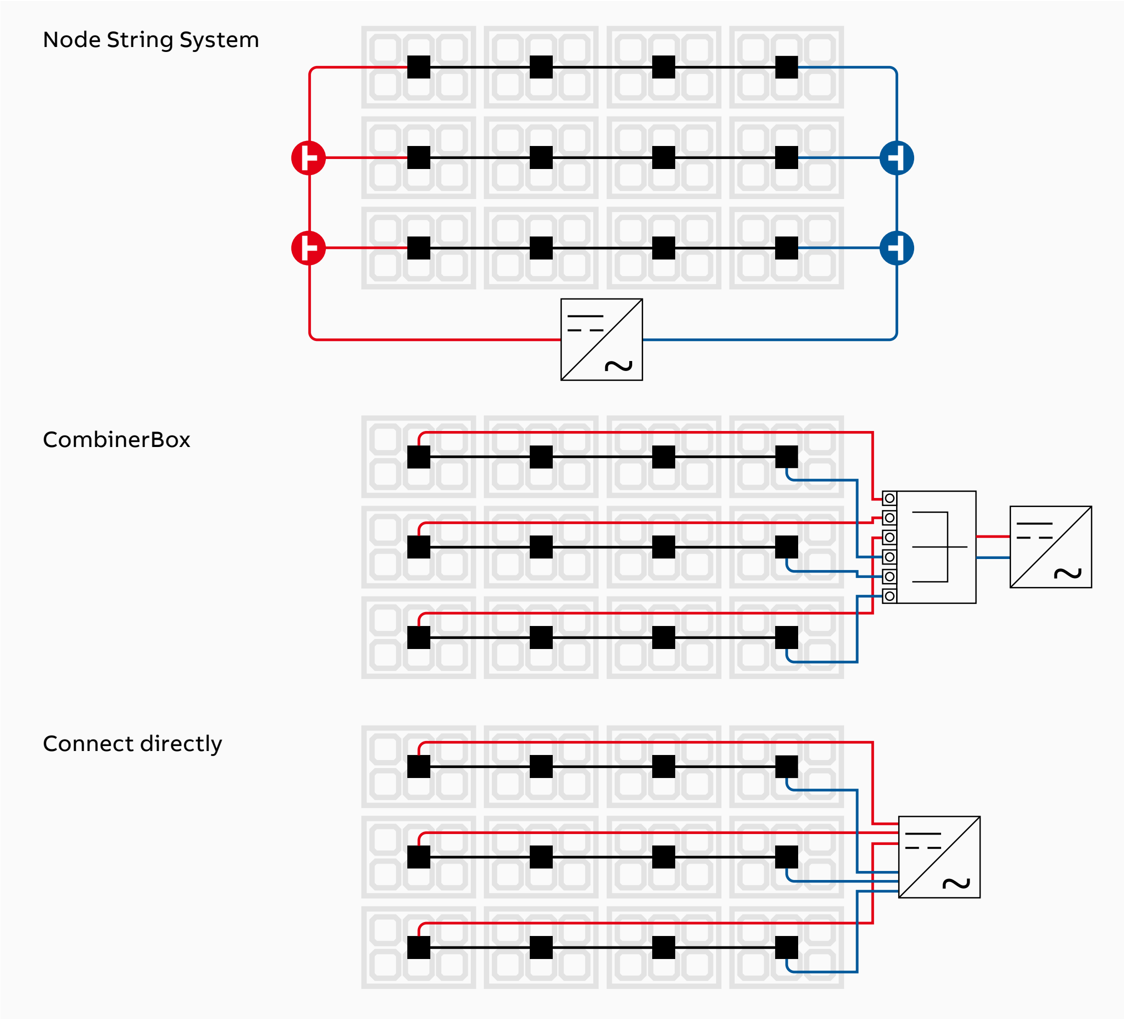
In addition to the requirements detailed in IEC 60364, segregation shall be provided between DC and AC circuits to the same requirements as for segregation of different voltage levels.

PV Strings interconnection

There are three types of designs to connect the PV strings to the solar power inverter:

- Node String system: it is common in the PV generator composed by thin-film PV modules;
- PV system with DC Combiner Box: this kind of connection is used in combination with central inverters;
- Direct Connection: this kind of connection is used in combination with small size of string inverters;

—
Figure 45
different types of designs to interconnect the PV strings



In case of node string system, the string interconnection is made with special type of branch or "Y" sockets and plugs.

—
Figure 46
socket and plug "Y" connectors: Branch socket in left side; Branch plug in right side

In case of PV system with DC Combiner Box, the PV strings cables that enter in the combiner boxes shall be grouped and identified in pairs so that positive and negative conductors of the same circuit may easily be clearly distinguished from other pairs.

3

DC Plug and Socket Connectors
PV specific plug and socket connectors are commonly fitted to PV module cables by the PV modules manufacturer. Such connectors provide a durable, secure and effective electrical contact.
In accordance with IEC 60364-7-712, these DC Plug and Socket Connectors shall be selected in accordance with IEC 62852 “Connectors for DC-application in photovoltaic systems - Safety requirements and tests”.

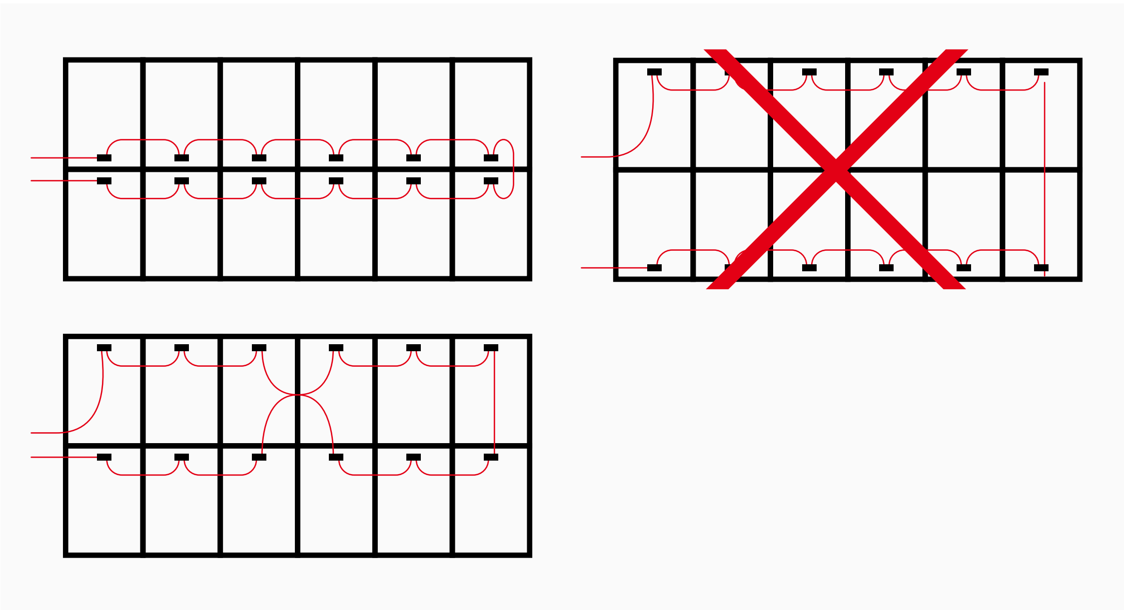
—
Figure 47
plug and socket
connectors

The connectors shall be handled by skilled or instructed persons and shall be never be disconnected under load; in case of disconnection under load, a DC arcing could be triggered and the arcing can cause permanent damage to the connectors. The connectors shall be of a type which can only be disconnected by means of a key or a tool or be installed within an enclosure which can only be opened by means of a key or a tool.

Plugs and socket connectors mated together in a PV system shall be of the same type from the same manufacturer and shall comply with the requirements of IEC 62852. In case of use of different brands of plug and socket “compatible” connectors, they may only be interconnected where a test report has been provided confirming compatibility of the two types to the requirements of IEC 62852.
All the plug and socket connectors used in a PV string circuit (PV module interconnection, inline cable junctions, branch or “Y” sockets and plugs and panel-receptacle connectors) must comply with the minimum voltage and current ratings as detailed above in string cables selection.

PV modules interconnection and strings cabling
IEC 60364-7-712 require that, in order to minimize induced voltages due to lightning, the surface of all loops shall be as small as possible, in particular for the wiring of PV strings.

—
Figure 48
e.g. of PV string wiring
in order to minimize
induced voltages
due to lightning



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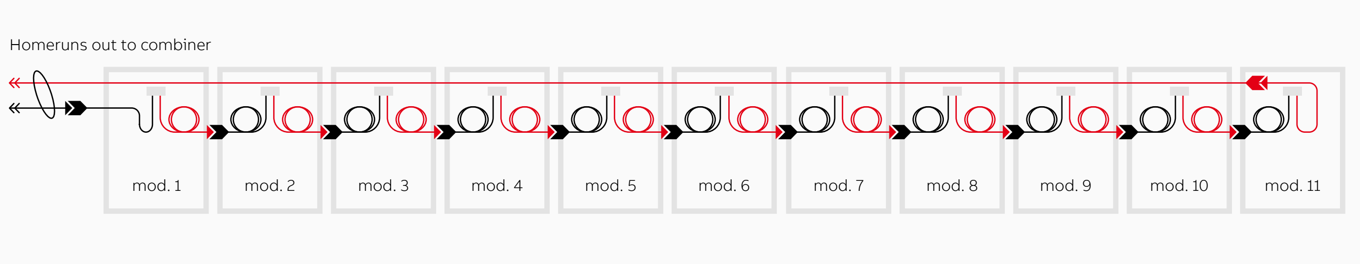
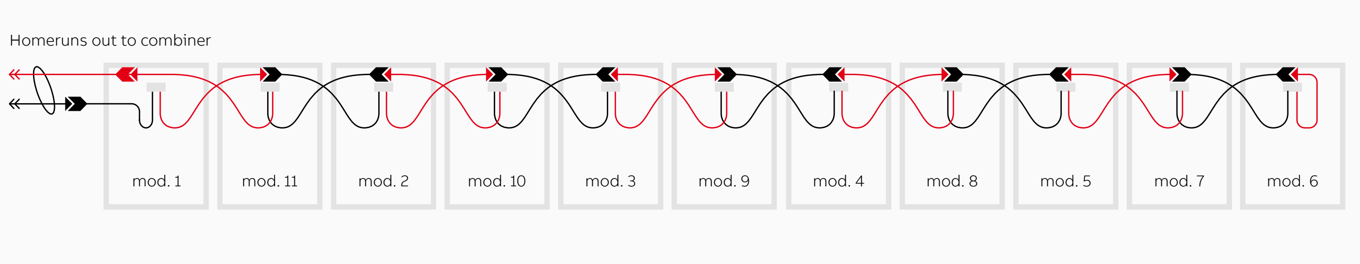
Anyway, it is recommendable to verify if the PV modules installation and maintenance manual there are restriction about the PV modules installation (e.g. some PV modules manufacturer doesn't allow the portrait-oriented PV modules installation with junction box positioned in the bottom side in order to avoid standing water near to the junction box). Standard practice for module-to-module wiring is to connect adjacent modules in a daisy chain. Excess module cables length is often coiled up and organized using some clips or tapes.

—
Figure 49
e.g. of PV string wiring in daisy chain with coiled up cables



—
Figure 50
e.g. of PV string wiring in leapfrog wiring

Given adequate module cables length, leapfrog wiring can be used to connect portrait-oriented PV modules in series and avoiding coiled up cables.



Anyway, it is highly inadvisable to pile up and fix the cables inside the metal frames of PV modules fixing system.

3.4.2 Cables cross-sectional area and current carrying capacity

Cables shall be sized in accordance with IEC 60364-5-52 "Low-voltage electrical installations - Part 5-52: Selection and erection of electrical equipment - Wiring systems" and in accordance with the requirements of IEC 60364-7-712. These calculations shall also take into account operation condition of the cables in terms of voltage and current.

PV modules string cables

The voltage rating of a cable refers to the maximum voltage to which it may be connected.
If the voltage rating is exceeded, the insulation between cable cores, or between a cable core and earth, may break down and cause a short-circuit or a fire. The cables voltage rating shall be chosen according to the maximum open circuit voltage ($V_{oc\ MAX\ string}$) of the strings. According to the number of PV Modules per string the maximum open circuit voltage ($V_{oc\ MAX\ string}$) of the string can be calculated using the following data:

- lowest temperature that can be expected at the PV installation location;
- PV module open circuit voltage at STC condition $V_{oc\ STC}$;
- PV module temperature coefficient.

Otherwise, for wire sizing, a voltage multiplication factor could be used:

—
Equation 42

$$V_{OC\ MAX\ string} = V_{OC\ STC\ string} \cdot 1.15$$

The continuous current-carrying capacity I_z of the PV string cables shall be greater than or equal to the short-circuit maximum current of the string for the protection against overload current of the PV string cables.

—
Equation 43

$$I_z \geq I_{sc\ MAX\ string}$$

3

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As already introduced in the paragraph 1.2.1, in a series connection of modules the current does not add up; the total current in a string of PV modules connected in series is equal to the current generated by the single module. The maximum string short-circuit current $I_{sc\ MAX\ string}$ is equal to the maximum PV module short-circuit current $I_{sc\ MAX\ module}$ and, as already introduced in the paragraph 2.9.2, it can be calculated using the following data:

- maximum temperature that can be expected at the PV installation location;
- PV module short-circuit current at STC condition $I_{sc\ STC}$;
- PV module temperature coefficient.

Otherwise, for wire sizing, a current multiplication factor could be use:

—
Equation 44

$$I_z \geq I_{sc\ MAX\ string} = I_{SC\ STC\ string} \cdot 1.25$$

Guidance on a method of cable sizing including any de-rating factor requiring to be applied and typical current carrying capacities for common cable types are provided in IEC 60364-5-52. In any case, cables shall be sized such that the overall voltage drop, at array maximum operating power (STC), between the array and the combiner box or inverter is <3%.

Array cables

As already introduced in the paragraph 1.2.1, in a parallel connection of strings:

- the voltage is the same over all PV modules strings;
- the currents of PV modules strings add up.

Then, the array and sub-array cables voltage rating shall be chosen according to the maximum open circuit voltage ($V_{oc\ MAX\ string}$) of the strings as already introduced above for PV modules string cables.
The continuous current-carrying capacity I_z of the PV array cable shall be greater than or equal to the maximum direct current of the PV array for the protection against overload current of the PV array cables.
In a PV array composed by N strings, the maximum direct current of the PV array is equal to the add up of the maximum direct current of the PV strings.

—
Equation 45

$$I_z \geq I_{sc\ MAX\ array} = N \cdot I_{sc\ MAX\ string} = N \cdot I_{SC\ STC\ string} \cdot 1.25$$

Guidance on a method of cable sizing including any de-rating factor requiring to be applied and typical current carrying capacities for common cable types are provided in IEC 60364-5-52. In any case, cables shall be sized such that the overall voltage drop, at array maximum operating power (STC), between the array and the inverter is <3%.

3

MV side of PV plant

MV side of PV plant

4.1 Network schemes

In case of utility scale PV plant directly connected to the DSO MV grid, the designer shall size also the MV electric network of the PV plant correctly; it is necessary to do the following network calculations either entirely or partly:
- sizing calculations (transformers, etc.);
- calculation of the short-circuit currents;
- definition of the status of the neutral;
- study of protection coordination.

Before all these activities, the single-line diagram of the PV plant MV electric network shall be defined on the basis of:
- inverter and transformer position;
- electric network structure.

The advantages and disadvantages of the different MV network solutions shall be considered and, after that, according to the PV plant MV electric network designed, also the protections shall be selected. For more detailed information about the MV connection, it is recommended to refer to the ABB Technical guide about MV applications

4.1.1 Radial network

This is the simplest, least costly network scheme and the one with least overall reliability.

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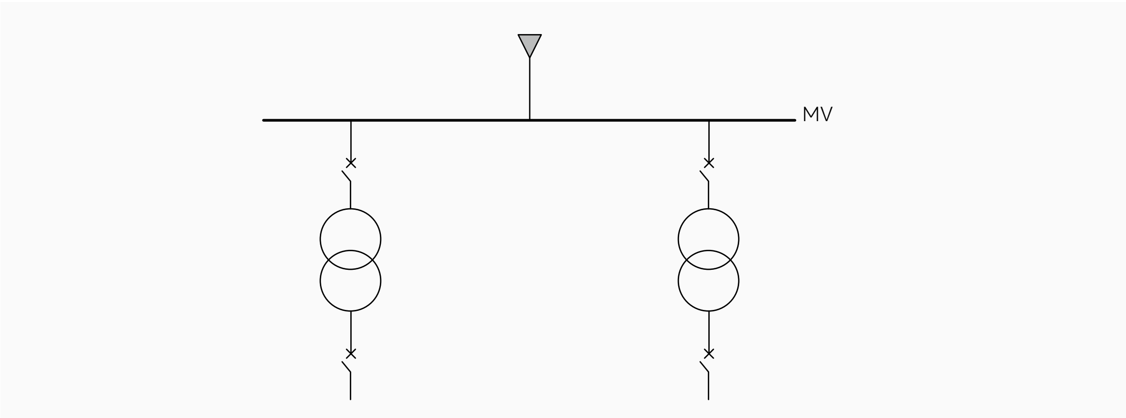
Figure 51
MV radial network

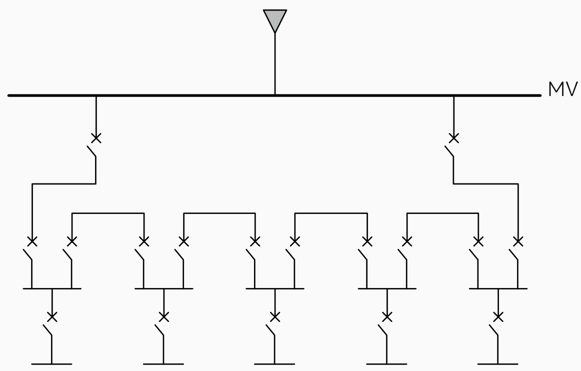


In a PV system with multiple (>2) PV plant substation is the most simple and economic solution.

4.1.2 Ring network

Ring networks make it possible to always have two power supplies for each PV plant substation. In practice, the ring scheme is characterised by the presence of at least one side more (n+1) compared with the minimum needed to connect the PV plant substation to the power supply node.

Figure 52
MV ring network



The main advantages of ring networks equipped with protections and circuit-breakers on the in-out of each substation are:

- service continuity, i.e. the possibility of only eliminating from service the part of the network where the fault is, keeping the remaining part of the ring in operation;
- the possibility of carrying out maintenance on parts of the plant without causing out of services or plant stoppages.

On the other hand, the disadvantages are:

- realisation costs linked to the extension of the network;
- complexity of the protection system.

4.2 Selection of switching devices

There are three main types of electric circuit opening and closing devices which are used in medium voltage networks.

- Circuit-breakers: apparatus able to close and interrupt the short-circuit current.
- Contactors: apparatus able to carry out a high number of operations and interrupt limited short-circuit currents.
- Switch-disconnectors: switch-disconnectors or isolators able either to open the rated current or not (obviously with a high-power factor) guaranteeing the galvanic isolation.

Together with the devices mentioned previously, the fuses which are associated both with the contactors and often also with the switch-disconnectors, must also be considered. In the PV power plant, the use of MV circuit-breakers is compulsory when differential protections and other protections which have instantaneous trip are to be used for rapid elimination of the fault.

4.3 Instrument transformers (ITs): Current transformers (CTs) and Voltage transformers (VTs)

Instrument transformers (ITs)[17] are designed to transform voltage or current from the high values in MV systems to the low values that can be utilized by low voltage metering devices.
The main applications of ITs in the PV plant are:
• metering (for energy billing and transaction purposes);
• protection control (for system protection and protective relaying purposes).
Depending on the requirements for those applications, the IT design and construction can be quite different. Generally, the metering ITs require high accuracy in the range of normal operating voltage and current. Protection ITs require linearity in a wide range of voltages and currents.
Protection ITs shall be selected according to the requirements of grid codes[18].

17
ABB Instrument Transformers Technical Information and Application Guide contains detailed information about ITs.

18
National grid code shall be verified in any case.

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4.3.1 Inductive transformers

The construction characteristics and definition of the precision classes are given in international Standards. It must be considered that the precision class for instrument CTs and VTs and protection VT, is a function of the load connected to the secondary: precision is only guaranteed when the secondary load is higher than 25% of the rated performance of the transformer.
Considering the present low consumptions of the apparatus connected to the secondary, it is therefore essential for the performance of the VTs (both of measurement and of protection) as well as of the instrument CTs to be limited to guarantee that the transducer operates in the precision class for which it has been provided.

4.3.2 Inductive current transformers (CTs)

An important clarification must be made regarding the CTs relative to their construction shape and to the method of measurement. This refers particularly to ring CTs which are CTs to all effects and must be classified as such.
The CT can be of:

- wound type (as CTs inside medium voltage switchgear normally are), with the two terminal clamps of the primary circuit and the two terminal clamps of the secondary circuit taken outside. The primary circuit can, in this case, also have a number of turns different from 1;
- busbar bushing type where there is a piece of busbar (normally made of copper) already embedded in resin. In this case, the terminals of the primary winding are the ends of the busbar, whereas the ends of the secondary winding are taken to external terminals. In any case, the number of primary turns in this case is always 1;
- ring type where the primary is not provided and it will be made up of the conductor which passes through the central hole of the CT. The ends of the secondary winding are taken to two external terminals. In this case the number of primary turns is in any case normally 1 unless the conductor is made to pass several times in the CT. These CTs can also be constructed as the openable type for easier installation in existing plants.

The precision classes are the same for all the types of CTs, and are defined in accordance with the Standard. According to how the CT is inserted in the network, it can carry out very different measurements. In particular:

- the CT which is inserted on just one phase (for example, a ring CT which embraces just one phase) measures line currents (of phase);
- the CT which is inserted on three phases (for example, a ring CT which encloses the conductors of the three phases inside it) measures the vectorial sum of the currents (in reality the sum of the flux) and therefore the zero-sequence current.

What has previously been underlined is to indicate that regardless of the construction shape, the measurement which is obtained at the secondary of the CT is a function of the way in which it is inserted in the network.
The CTs serve to translate currents from the power circuit to the measurement circuit.
They are classified into two types by the Standard:

- instrument CTs measuring instruments, such as ammeters, watt meters, converters, etc. are connected to;
- Protection CTs to whose secondary the protection relays are connected.

This classification refers to independent measurement and protection systems. Nowadays with digital apparatus, protection and measurement are carried out by the same piece of apparatus and separate inputs[19] (measurement and protection) from CTs with different characteristics are not provided. Consequently, to obtain correct use of the digital relays, the CTs must be chosen with double precision class.

—
19
In any case the energy metering requirements for the ITs shall be verified.

4.3.3 Inductive voltage transformers (VT)

For voltage transformers, both for measurement instruments and for protection relays, the same rule as the one for the instrument CT is valid regarding the range within which the precision class is guaranteed: the precision class is only guaranteed if the secondary load is 25% higher than the rated performance.
It is not easy to manage to ensure that a VT operates in the precision class when an instrument is connected to the secondary (relay or measurement instrument) which has a self-consumption of fractions of VA.
The use of ballast loads (resistances) to be inserted on the secondary of the VT when these have been chosen with performances which are too high to be able to guarantee the precision class, presents two problems:
- an element is added to the circuit (which can also be for protection) which can break down and therefore reduce the overall reliability of the system;
- a heating element is introduced in the instrument compartments of the switchgear with obvious problems for extracting the heat.

When selecting the VT, any ferroresonance must be taken into account. The ferroresonance phenomenon is a typical aspect of VTs inserted in cable networks with isolated neutral or not efficiently grounded. The cable capacity, together with the VT inductance, makes up an oscillating circuit (R L C). The conditions for which the circuit itself goes into resonance can therefore occur on the circuit (capacitive reactance = inductive reactance saturates the VT) and, although the cause of the saturation ceases (for example, a ground fault), a transient oscillation remains (i.e. a multiple frequency of that of the network) of reactive energy put into play by the components of the oscillating circuit. Owing to the frequency of this oscillation, a permanent and high circulation of current is produced just in the primary winding. Since this current is only magnetising, the secondary winding is little involved, so there is a lot of heating at the primary and negligible heating on the secondary. Abnormal heating of the windings always produces a strong internal pressure, consequently breaking the external housing.
The measures taken to prevent ferroresonance phenomena are mainly to:
- increase the magnetisation impedance of the VT;
- use VTs which work with lower induction than the predicted one;
- use VTs with high permeability iron;
- insert damping resistances (or, in any case, devices with non-linear resistance) in series with the secondary windings connected with open delta (the voltage relay must be connected in parallel with the anti-ferroresonance resistance).

Sometimes, depend from the national standard, a secondary set of three VTs connected with open delta are used to measure the zero-sequence voltages (needed to identify the ground faults).

4.3.4 Non-inductive current and voltage sensors

Since the power absorbed by the devices connected to the secondary circuit is extremely limited, it is no longer necessary to have magnetic circuits for the coupling between the primary and secondary circuit. Current sensors or air CTs (Rogowsky coils) and voltage sensors (voltage dividers) have therefore been developed, which eliminate the negative aspects of the inductive type of transformers (hysteresis cycle).
Particular reference is made to:
- saturation: the saturation phenomenon does not exist with current sensors (there is no iron) and therefore definition of the ultimate precision factor is no longer a problem;
- performance: the previous examples showed how difficult it is to reconcile the performance of the instrument transformers with the loads connected to the secondary. In fact, the need to have at least 25% of load to guarantee precision is no longer a problem;
- rated primary currents and voltages: the linearity of response allows 95% of the applications to be covered with just two or three types of transducers, with considerable advantages for standardisation of the switchgear compartments and the possibility of their rapid re-conversion;
- there is no longer the need to have instrument CTs or VTs and/or Protection CTs or VTs since precision is constant and there is no longer the problem of saturation.

For current sensors or air CTs, the main characteristic is that these are transformers whose magnetic circuit is replaced by air. A peculiar fact about these types of CTs is that the secondary signal is not proportional to the primary size, but to its derivative (which, when suitably integrated in the devices connected to the secondary, allows current measurement to be obtained). As already pointed out, there

are no saturation phenomena, but as a negative aspect there generally the precision class, which in present-day design does not reach the characteristics which can be had for the inductive type of instrument CTs.
The main characteristic for the voltage sensors is the lack of ferroresonance phenomenon (obviously because there is no longer any iron). This is not a negligible advantage where there is still the use of networks run with isolated neutral. As for air CTs, in the current state of technology, the precision class of voltage dividers (VTs) does not yet reach that of the inductive type of VTs either.

4.4 Short-circuit

The connection of the PV plant to the grid must be designed in a way to safely withstand the mechanical and thermal effects of short-circuit currents. The characteristic values for dimensioning the connection system are typically provided by the grid operator at the grid connection point (for example, rated voltages and rated short-time current).
The Short-circuit is accidental or intentional contact, with relatively low resistance or impedance, between two or more points at different voltages in a circuit. The Short-circuit current is an overcurrent resulting from a short-circuit due to a fault or to incorrect connection of an electric circuit.
From the theoretical point of view, calculation of the short-circuit currents should be processed using the data obtained from studying the voltage profiles. By the way, the Standards envisage that the calculation be made at the rated plant values and appropriate correction coefficients are introduced for compensation (voltage factor ‘c’).
The short-circuit currents calculation is necessary to:
- establish adequate sizing of the operating and interruption parts;
- define the thermal and mechanical stresses of the plant elements;
- calculate and select the protection system settings;
- carry out suitable protection for people and the plants.

The short-circuit currents under the various different operating conditions shall be define in the study of an electric system:
- the maximum short-circuit currents are important for system sizing;
- the minimum short-circuit currents are important in order to protection coordination (the protection trip current must always be lower than the minimum short-circuit current at the point of connection).

Four different types of grid faults of MV power transmission line:
- single-phase grounded fault;
- two-phase short-circuit fault;
- two-phase grounded fault;
- three-phase short-circuit fault.

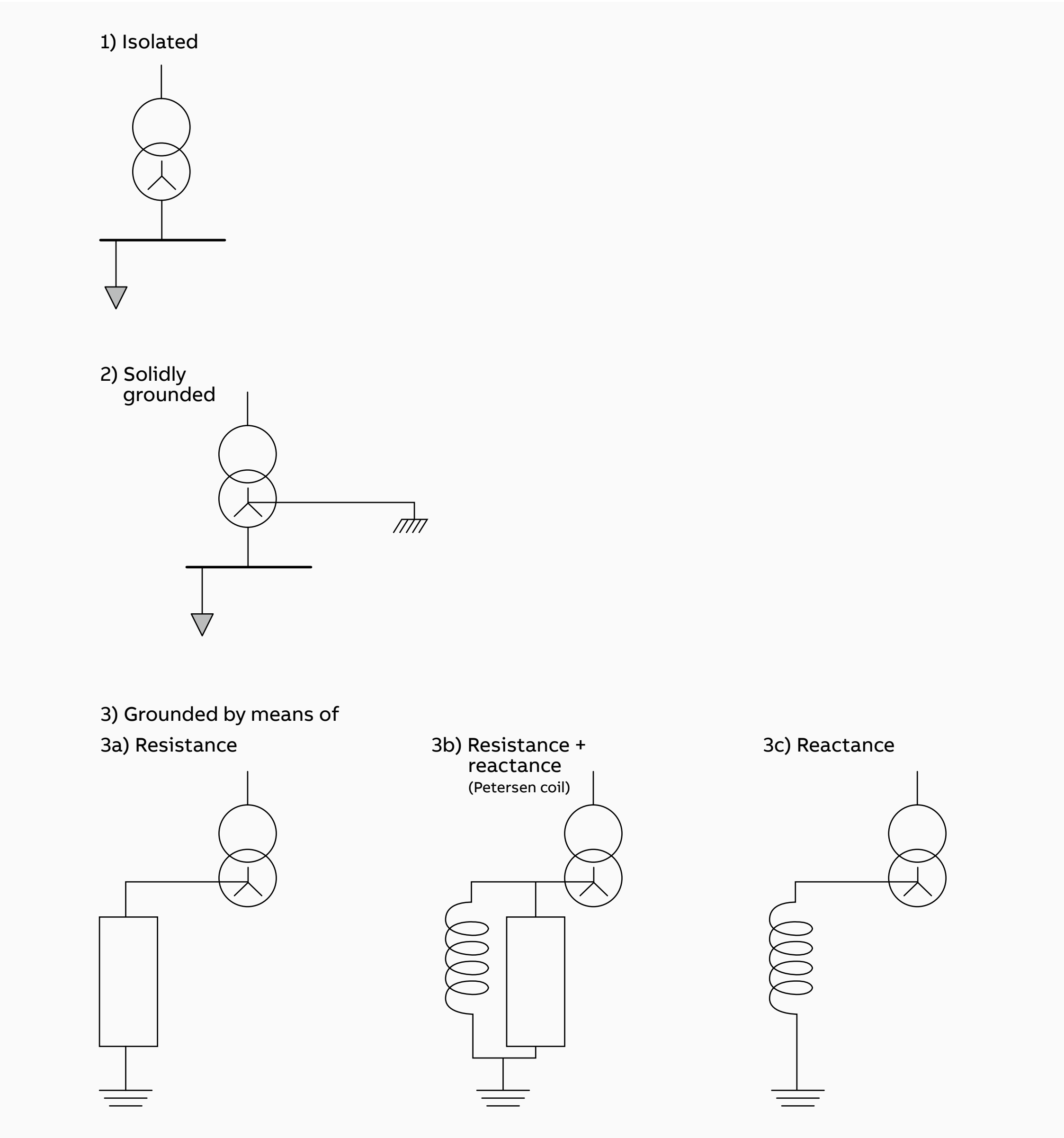
The most common one is the single-phase grounded fault, which accounting for over 90 % of the total number of the faults.
The short-circuit causes passage of currents through the accidental or intentional connection making up the short-circuit itself and through the various components as far as the source: it is therefore a potential cause of damage and fires.
The grid integration of PV plants influences the short-circuit capacity (SCC) of power systems.
The behaviour of PV plant is different from that of classical synchronous generators during symmetrical or unsymmetrical short-circuits. The response of PV plants to short-circuits is usually controlled by the power electronics used in inverters.
During grid failures, according to the grid codes, the PV plant shall remain connected to grid and the reactive current control of the generation unit shall be used to support the grid voltage in case of short-term voltage drop or increase (Fault Ride Through operation mode).
In this situation the PV inverters may generate currents that are slightly above the maximum current in normal operating conditions. The current level reached in these conditions is relevant for the correct sizing of the wiring and protective devices, both at PV power plant and grid level.

4.5 Status of the neutral

To identify ground faults in a network and therefore carry out effective protection, it is necessary to know in detail how the neutral is run. Identification of ground faults is made by means of voltage and/or zero-sequence current measurements and therefore knowing the existence and order of these parameters is fundamental in being able to select and set the protection system.
Unlike the protections against overload or polyphase short-circuit, no signal (voltage or current) normally comes to the protections which have to identify ground faults, but, on the other hand, only comes when there is a ground fault in the network. This condition makes the protection system to be provided very simple, generally only requiring one threshold (voltage and/or current) with relatively short trip times.
By analysing the various types of status of the neutral, the types of protections which can be associated can be defined.

4

Figure 53
Status of the neutral



4.5.1 Isolated neutral

In networks with isolated neutral, no circulation of zero-sequence current is generated deliberately (by means of grounding systems) in the case of a fault between a phase and ground. However, there is a circulation of zero-sequence current in the plant linked to the phase ground capacities of the inverters and cables (for what regards the transformers, the phase to ground capacities are very small and they can be overlooked).
The difficulty (in any set-up the network may be found to run in) of being able to identify ground faults using selective protections which measure the fault current can be deduced from this.
The only way to be able to ensure identification of the fault is measurement of the zero-sequence voltage (voltage normally equal to zero in the absence of a fault and different from zero only in the presence of a phase to ground fault).
Unfortunately, the voltage zero-sequence protection (like all voltage protections for that matter) is not of the selective type and then it is not able to identify the position of the fault; it is only able to indicate that there is a fault in the network without specifying its position.
Zero-sequence current, zero-sequence voltage and angle between voltage and zero-sequence current in a network are:

- zero-sequence current only from capacitive contribution (operation of the metallically interconnected network) of variable value in any case and, in general, not guaranteed for all the conditions the network can be run in. Identification of the faults is not always certain by means of zero-sequence current measurements;
- zero-sequence voltage always presents in the case of a ground fault. It is therefore definite identification but with uncertainty linked to the position of the fault since the voltmetric signal is practically the same for the whole network and does not allow selective identification;
- angle between voltage and zero-sequence current: the current is in advance by 90° compared with the voltage (capacitive type of network).

4.5.2 Solidly grounded neutral

With solidly grounded neutral, the single-phase to ground fault current is in the same order of size as the short-circuit current for polyphase faults. Consequently, simple and selective identification of the faults by means of protections which measure the zero-sequence current is possible
(or the zero-sequence protection could even be omitted and only the phase protection used).
Zero-sequence current, zero-sequence voltage and angle between voltage and zero-sequence current in the network are:

- zero-sequence current of high value. Therefore, identification of the faults by means of measuring the current is always certain and of selective type (the part of the network seat of the fault can be identified correctly);
- zero-sequence voltage: if this voltage is measured between star point and ground, the voltage is null, whereas, if the vectorial sum of the three phase voltages is measured, this is different from zero and gives indication of a fault in the network (but not of selective type);
- angle between voltage and zero-sequence current: the current is late (typical values 75-85°) compared to the voltage (inductive type of network source).

4.5.3 Neutral grounded by means of resistance

Grounding the neutral by means of resistance allows a definite current to be obtained in the case of a fault and consequently to be able to carry out selective protection of the network.
Depending on the value of the resistance installed, fault current values which are higher or less high are obtained.
Zero-sequence current, zero-sequence voltage and angle between voltage and zero-sequence current in the network are:

- zero-sequence current of known value. Identification of the faults is possible by measuring the zero-sequence current. The protection is therefore of the selective type;
- zero-sequence voltage: if this voltage is measured between the star point and ground, the voltage varies according to the value of the grounding resistance (for grounding resistances of high value one falls back into the situation of isolated neutral, for grounding resistances of very small value, one falls back into the situation of solidly grounded neutral). If the vectorial sum of the three phase

voltages is measured, it is different from zero and gives indication of a fault in the network (but not of the selective type);
- angle between voltage and zero-sequence current: theoretically equal to zero (in phase).

There are various methods to create network grounding according to the availability or lack thereof of the star point as shown in the figure 53.

4.5.4 Neutral grounded by means of impedance (Petersen coil)

Grounding the neutral by means of impedance allows the network capacitive currents to be compensated and therefore to reduce the current to relatively small values in the case of a fault and with a fault angle about equal to zero (compensated network).
Zero-sequence current, zero-sequence voltage and angle between voltage and zero-sequence current in network are:
- zero-sequence current of known value. Identification of the faults by means of zero-sequence current measurement is possible. The protection is therefore of the selective type;
- zero-sequence voltage: the measurement of the vectorial sum of the three phase voltages is different from zero and gives indication of a fault in the network (but not of the selective type).
- angle between zero-sequence voltage and current: theoretically equal to zero (network tuned). In actual fact, the angle can in any case diverge slightly both in advance and delayed according to the setting of the compensation reactance and to changes in the network set-up.

4.6 Measurement of the ground fault current and identification of the faulted phase

Since the advent, first of electronic and then of digital protections which have low absorption on the current circuit, the use of ring type CTs has been possible (able to generally give very small performances), which allows the vectorial sum of flux to be measured instead of the vectorial sum of the three currents (residual connection). When a zero-sequence over current protection is connected to the residual connection of the phase CTs (Holmgreen connection) it performs a vectorial sum of the currents and the resultant is therefore affected by the aperiodic components linked to magnetisation of the transformers. In this case, very conservative settings of the protections are required and the stability of these is not normally guaranteed (risk of unwanted trips). It is therefore suggested to systematically use (obviously where possible) CTs of ring type associated with the zero-sequence overcurrent protection.
In the case where it is necessary to identify which of the phases is the seat of the ground fault, identification is possible using undervoltage protections with measurement for each independent phase connected between the phase to ground (obviously to the VT secondary).

4.7 Protection relay codes

The protection of the connection point of PV plants is of considerable importance for the safe and reliable operation of the overall network. Often it is mandatory to have automatic devices for switching off short-circuits. The plant operator often is responsible for the reliable protection of his plants against e.g. short-circuits, ground faults, overloads, protection against electric surges, etc.
The ANSI standard device numbers (ANSI /IEEE Standard C37.2 Standard for Electrical Power System Device Function Numbers, Acronyms, and Contact Designations) identifies the features of a protective device such as a relay or circuit-breaker. Device numbers are used to identify the functions of devices shown on a schematic diagram. The standard gives also function descriptions.

1 Master Element
2 Time Delay Starting or Closing Relay
3 Checking or Interlocking Relay
4 Master Contactor
5 Stopping
6 Starting circuit-breaker
7 Rate of Change Relay
8 Control Power Disconnecting Device
9 Reversing Device
10 Unit Sequence Switch
11 Multi-function Device
12 Overspeed Device
13 Synchronous-speed Device
14 Underspeed Device
15 Speed – or Frequency, Matching Device
16 Data Communications Device
17 Shunting or Discharge Switch
18 Accelerating or Decelerating Device
19 Starting to Running Transition Contactor
20 Electrically Operated Valve
21 Distance Relay
22 Equalizer circuit-breaker
23 Temperature Control Device
24 Volts Per Hertz Relay
25 Synchronizing or Synchronism-Check Device
26 Apparatus Thermal Device
27 Undervoltage Relay
28 Flame detector
29 Isolating Contactor or Switch
30 Annunciator Relay
31 Separate Excitation
32 Directional Power Relay or Reverse Power Relay
33 Position Switch
34 Master Sequence Device
35 Brush-Operating or Slip-Ring Short-Circuiting Device
36 Polarity or Polarizing Voltage Devices
37 Undercurrent or Underpower Relay
38 Bearing Protective Device
39 Mechanical Condition Monitor
40 Field (over/under excitation) Relay
41 Field circuit-breaker
42 Running circuit-breaker
43 Manual Transfer or Selector Device
44 Unit Sequence Starting Relay
45 Abnormal Atmospheric Condition Monitor
46 Reverse phase or Phase Balance Current Relay
47 Phase Sequence or Phase Balance Voltage Relay
48 Incomplete Sequence Relay
49 Machine or Transformer, Thermal Relay
50 Instantaneous Overcurrent Relay
51 AC Inverse Time Overcurrent Relay
52 AC circuit-breaker
53 Exciter or DC Generator Relay
54 Turning Gear Engaging Device
55 Power Factor Relay
56 Field Application Relay
57 Short Circuiting or Grounding Device
58 Rectification Failure Relay
59 Overvoltage Relay
60 Voltage or Current Balance Relay
61 Density Switch or Sensor
62 Time Delay Stopping or Opening Relay
63 Pressure Switch
64 Ground Detector Relay
65 Governor
66 Notching or Jogging Device
67 AC Directional Overcurrent Relay
68 Blocking Relay
69 Permissive Control Device
70 Rheostat
71 Liquid Level Switch
72 DC circuit-breaker
73 Load Resistor Contactor
74 Alarm Relay
75 Position Changing Mechanism
76 DC Overcurrent Relay
77 Telemetering Device
78 Phase Angle Measuring Relay or "Out of-Step" Relay
79 AC Reclosing Relay
80 Flow Switch
81 Frequency Relay
82 DC Reclosing Relay
83 Automatic Selective Control or Transfer Relay
84 Operating Mechanism
85 Communications, Carrier or Pilot -Wire Relay
86 Lockout Relay
87 Differential Protective Relay
88 Auxiliary Motor or Motor Generator
89 Line Switch
90 Regulating Device
91 Voltage Directional Relay
92 Voltage and Power Directional Relay
93 Field Changing Contactor
94 Tripping or Trip-Free Relay
95 For specific applications where other numbers are not suitable
96 Busbar Trip Lockout relay
97 For specific applications where other numbers are not suitable
98 For specific applications where other numbers are not suitable
99 For specific applications where other numbers are not suitable
150 Earth Fault Indicator
AFD Arc Flash Detector
CLK Clock or Timing Source
DDR Dynamic Disturbance Recorder
DFR Digital Fault Recorder
ENV Environmental Data
HIZ High Impedance Fault Detector
HMI Human Machine Interface
HST Historian LGC Scheme Logic
MET Substation Metering
PDC Phasor Data Concentrator
PMU Phasor Measurement Unit
PQM Power Quality Monitor
RIO Remote Input / Output Device
RTU Remote Terminal Unit / Data Concentrator
SER Sequence of Events Recorder
TCM Trip Circuit Monitor

Suffix letters or numbers may be used with device numbers to indicate zone of protection.

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The suffix "N" is used if the device is connected to a neutral wire.
The suffix "G" is used to denote a "ground" or "generator".
Apart from the N and G suffixes, sometimes other suffixes are added to indicate the application of the protection in detail. For example:

- G generator (for example 87G differential protection for generator);
- T transformer (for example 87T differential protection for transformer);
- M motor (for example 87M differential protection for motor);
- P pilot (for example 87P differential protection with pilot wire);
- S stator (for example 51S overcurrent stator);
- LR motor protection against locked running rotor (51LR);
- BF failed opening circuit-breaker 50 BF (BF = breaker failure);
- R used for different applications:
  - reactance (for example 87R differential protection);
  - undervoltage to indicate residual voltage (27R);
  - rotor of a synchronous machine (64R ground rotor);
- V associated with the overcurrent protection (51) it indicates that there is voltage control or voltage restraint (51V);
- t indicates that the protection is timed (for example 50t protection against overcurrent short-circuit with delay added).

The electric protections are of different types and have different applications:

- zone protections (e.g. differential or with impedance);
- machine protections (e.g. reverse power);
- selective protections (e.g. overcurrent);
- on-selective protections (e.g. undervoltage, frequency);
- protections in support (e.g. fuses, overcurrent, undervoltage);
- interface protections (e.g. undervoltage protections; under/over and rate of change of frequency; overcurrent for disconnection between the plant network and the utility network);
- protections for making automatisms (e.g. synchronism check).

A PV production plant connected to the MV grid should be provided with: The devices[20] to be provided when a PV production system is grid connected are:

- General Device (GD), placed immediately downstream of the point of connection and capable of disconnecting the whole User's plant from the distribution grid. The GD can be realized by using either a MV three-pole circuit-breaker, withdrawable version, equipped with shunt opening release or a MV three-pole circuit-breaker, equipped with shunt opening release and MV three-pole switch-disconnector installed on the supply side of the circuit-breaker itself;
- Interface Device (ID), able to ensure both the disconnection of part of the User's plant (generators and possibly priority loads), thus allowing the loads to work in island-mode, as well as grid-connected operation;
- Generator Device (GenD), capable of excluding from the network the generating units only, separately. In case of LV generating units, the GenD can consist of an automatic circuit-breaker.

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20
A single device could perform different functions; in any case, for safety reason at least 2 devices shall be installed.

INDEX

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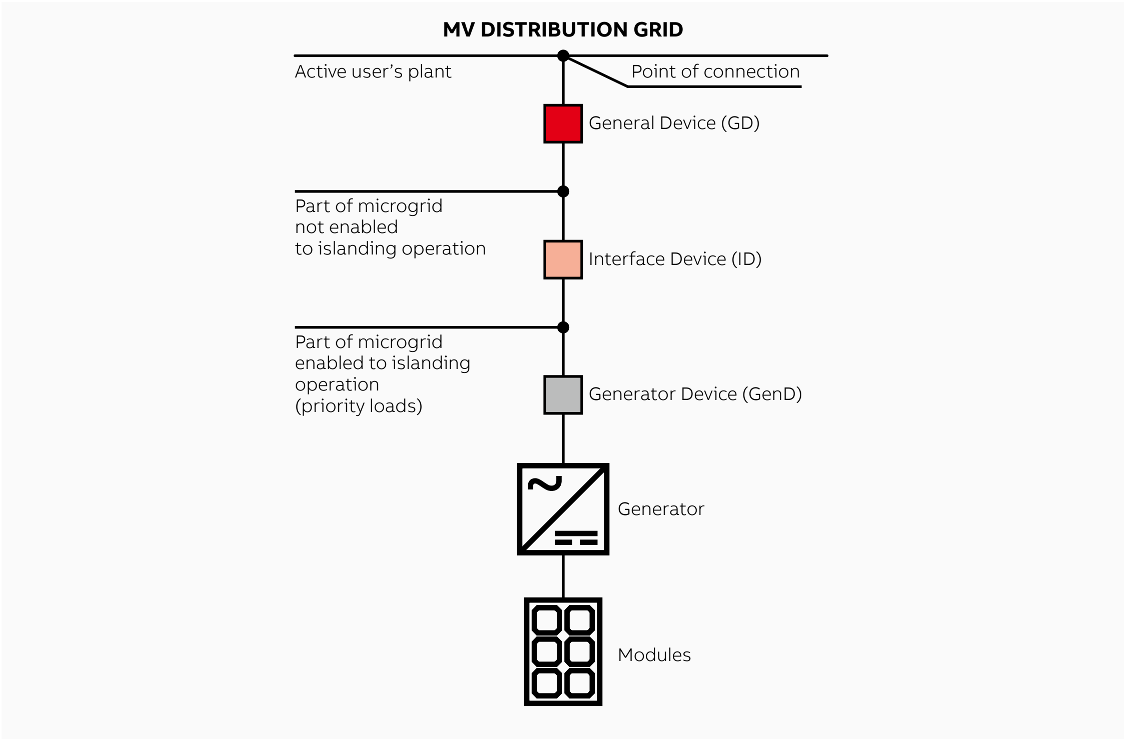
Figure 54
e.g. of protection implemented in the general protection



According to the above requirements, the following relays shall be set with the related protection functions.

- general protection system: protect the MV grid and its connected customers in case of faults in the PV plant is a duty of the General protection system;

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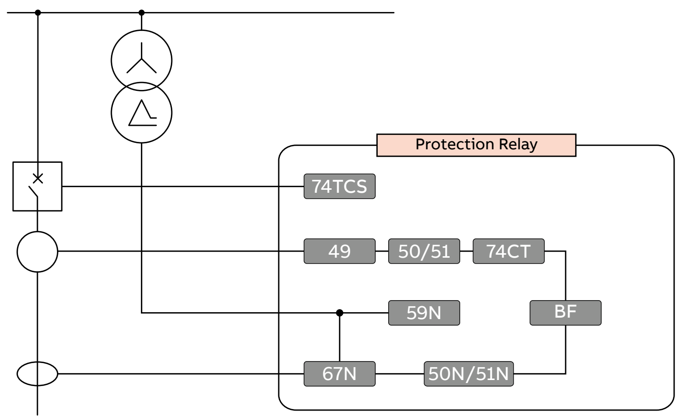
Figure 55
e.g. of protection implemented in the general protection



- Interface Protection System (IPS) (e.g. undervoltage protections; under/over and rate of change of frequency; overcurrent for disconnection between the plant network and the utility network): protect the PV plant in case of failures in the MV grid and disconnect the PV plant from the grid in case of DSO request are the duties of Interface Protection System;

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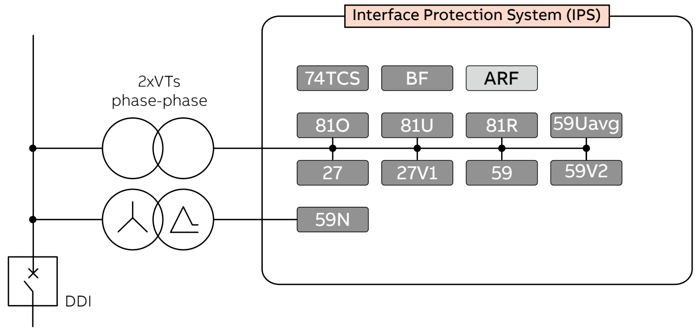
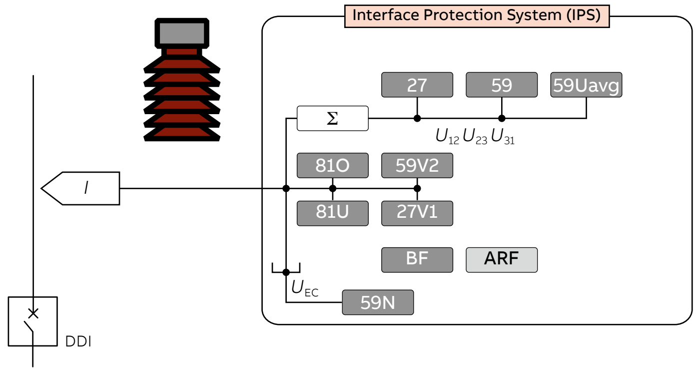
Figure 56
e.g. of protection implemented in the Interface Protection System





In case the PV system is designed with more than one MV/LV transformer, the transformer/ line protections relays shall be set with the related protection functions.

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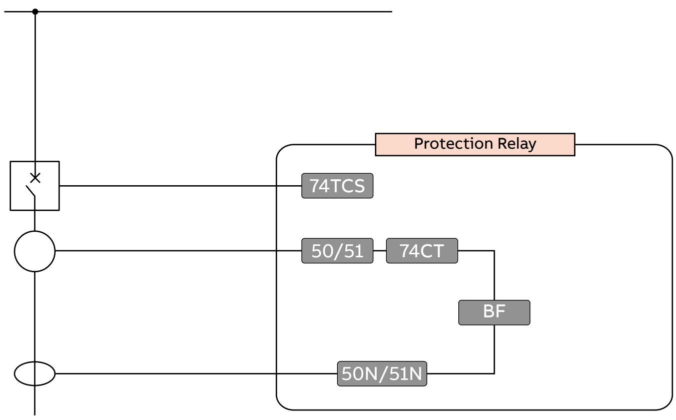
Figure 57
e.g. of protection implemented in the transformer/ line



4.8 Philosophy of protection settings

The objectives of the protection system are to:
- limit damage to people and to the plant;
- guarantee maximum service continuity for the plant not affected by faults;
- activate the automatisms provided.

The peculiar characteristics of the protection system of an electric network are:
- dependence: it can be called on to work after either a short or long period after installation. In any case, it must work when it is called on to operate;
- safety: it must not operate when is not required (it must not operate during transients). It must allow the various service conditions and activate the automatisms provided;
- selectivity: it must operate only and when necessary, guaranteeing maximum service continuity with minimum disconnection of the network; the selectivity could be:
  - Time selectivity: time type of selectivity is obtained by graduating the trip times of the protections (time discrimination or time selectivity) so that the relay closest to the fault trips in a shorter time compared to the ones further away.
  - Current selectivity: current type of selectivity is obtained by graduating the trip threshold of the protections to current values higher than those which can involve the load side protections (current discrimination or current selectivity).
  - Differential protection and distance protection selectivity: This kind of selectivity exploits the first law of Kirchoff at the node, i.e. the sum of the currents in a node must be equal to zero, if the summation of the currents is different from zero it means there is a fault.
  - Logical selectivity: Logical selectivity, also known as zone selectivity, is a selectivity criterion which was only introduced recently with the advent of digital protections. This selectivity criterion can be applied both to the overcurrent protections which identify phase faults, and to the overcurrent protections which identify ground faults.
- speed: represented by the minimum fault time;
- simplicity: measured by the number of pieces of equipment needed to protect the network;
- economy: assessed as the cost of the protection system in relation to the cost of malfunctioning.

A protection system is always the ensemble of:
- the instrument transformers (VTs and/or CTs)
- the relays with adequate settings.

The selection of the type of protection shell be made on the basis of:
- Grid code and standards;
- acceptable risk (consequences of the fault);
- short-circuit currents (maximum and minimum);
- status of the neutral;
- presence of self-production in plant;
- coordination with the existing system;
- coordination with the grid protection set by the DSO (Distribution System Operators);
- configurations and network running criteria;
- practices.

The aim is to achieve the best technical and economic compromise which allows adequate protection against “faults” with “significant” probability and to verify that the investment is commensurate with the importance of the plant.
In any case, for the protection selection, the national grid code shall be verified and the recommendation of the grid code shall be implemented.

Protection against electric shock, earthing and protection against indirect contact

5

Protection against electric shock, earthing and protection against indirect contact

5.1 Protection against electric shock - direct contact

Direct contact is defined as an event caused by a person getting in contact with a live conductor of the electrical installation.

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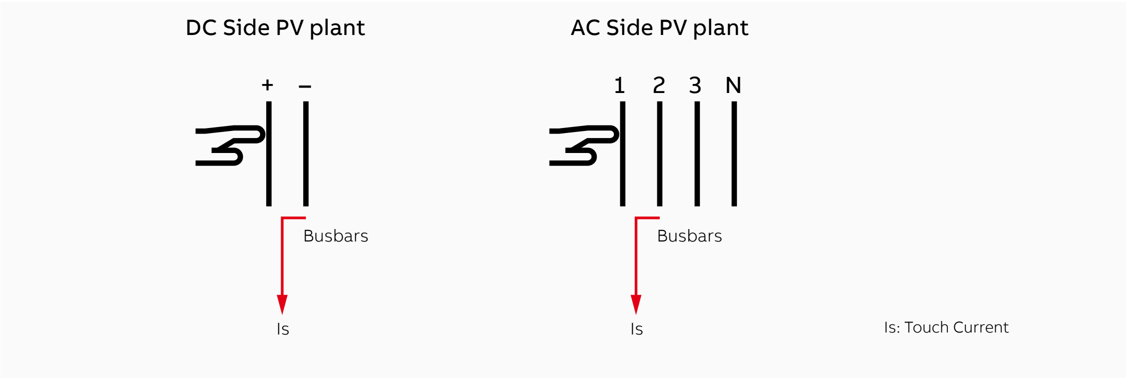
Figure 58
Direct contact representation



For protection against electric shock, in accordance with IEC 60364-7-712, on the DC side of the PV plant, one of the following protective measures shall be used:
- double or reinforced insulation;
- extra-low voltage.

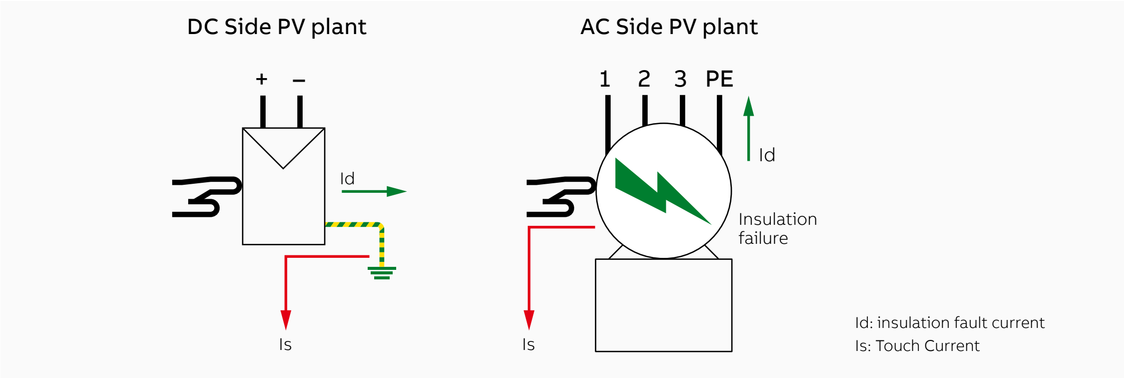
In the grid connected PV installation, considering the V_{oc} rating of the PV generator, usually the protective measure used against electric shock is the double or reinforced insulation[21]: then, all the equipment used on DC side up the terminals of the inverter (e.g. PV modules, combiner boxes, cables, etc.) shall be class II or equivalent insulation in accordance with IEC 61140 “Protection against electric shock – Common aspects for installation and equipment”. Direct contact protection is independent from the system earthing.

—
21
According IEC 60364-7-712 PV modules, wiring system used on the DC side shall be class II or equivalent insulation; IEC 60364-7-712 doesn’t exclude the use of Safety class I PV modules.

5.2 Protection against indirect contact

Indirect contact is defined as an event caused by a person getting in contact with an exposed-conductive-part. It is the result of an insulation fault that creates a fault current flowing.

—
Figure 59
Indirect contact representation



The world of electrical installations is not always straightforward: it can be divided in 2 areas for what concern electrical standards: IEC countries and NEC countries.
IEC 60364 is a collection of documents that define fundamental principles, practices, and performance requirements which reflect the European concept of wiring and distribution systems.

The NEC (National Electrical Code) is a set of specific rules intended to be used for design, installation, and uniform enforcement of electrical system installations based on North American principles and practices.

In order to provide safety of persons, livestock and property against danger and damage which may arise in the reasonable use of electrical installations, the International Electrotechnical Commission (IEC) provided the IEC 60364. The standard identifies three different characteristics of the distribution system:
- types of system earthing;
- types of system earthing of the exposed-conductive-parts of the electrical equipment;
- characteristics of the protective devices (tripping and alarm devices).

As result the following characteristics for the type of distribution system are identified:
- type and number of live conductors of the system[22];
- type of system earthing.

The coordination between types of system earthing and types of protective devices is always required by the protective measure.
IEC 60364 specifies a “Two Letter Codes” to identify type of earthing. The “Two Letter Codes” is based on Source Side – Device Side Earthing. The First Letter indicates how the Earthing is done on Source side (Generator / Transformer); the Second Letter indicates how the Earthing is done on Device side.
The used letters are as follows:
- “T”: it means direct connection of a point to earth;
- “I”: it means that either no point is connected to Earth or it is connected via high impedance;
- “N”: it means that there is direct connection to neutral at the source of installation which is in turn connected to the ground.

A subsequent letter to the “Two Letter Codes” identify the arrangement of neutral and protective conductors.
The used letters are as follows:
- “S”: protective function provided by a conductor separate from the neutral or from the earthed line (or in a. c. systems, earthed phase) conductor;
- “C”: neutral and protective functions combined in a single conductor (PEN conductor).

IEC 60364-5-54 defines three main standardized earthing systems schemes:
- TT system (earthed neutral - the source and the load separately connected to earth): in the installation, all exposed- and extraneous-conductive-parts are connected to a separate earth electrode;

—
22
IEC 60364 indicates the following conductor arrangement: single-phase 2-wire; single-phase 3-wire; two-phase 3-wire; three-phase 3-wire; three-phase 4-wire. NEC indicates the following conductor arrangement and installation system: single-phase 2-wire; single-phase 3-wire (split-phase), three-phase 4-wire Delta system; three-phase 4-wire Wye system; three-phase 4-wire Delta Hi-Leg system.

5

- TN systems (the neutral is earthed at transformer side only); exposed conductive parts connected to the neutral): in the installation, all exposed- and extraneous-conductive-parts are connected to the neutral conductor. The few versions of TN systems are indicated here below:
  - TN-C system: the neutral conductor is also used as a protective conductor and is referred to as a PEN (Protective Earth and Neutral) conductor; this kind of system is not allowed in case of conductors of less than 10 mm² or for portable equipment[23].
  - TN-S system: the protective conductor and the neutral conductor are separate. The TN-S system is mandatory in case of circuits with cross-sectional areas less than 10 mm² or for portable equipment[24].
  - TN-C-S system: The TN-C and TN-S systems can be used in the same installation. In the TN-C-S system, the TN-C (4 wires) system must never be used downstream of the TN-S (5 wires) system.
- IT system (isolated or impedance-earthed neutral)
  - IT system (isolated neutral)
  - IT system (impedance-earthed neutral)

23 On TN-C system the interruption/break of the neutral conductor is prohibited.

24 On TN-S system the neutral conductor could be interrupted; the protective conductor couldn't be interrupted.

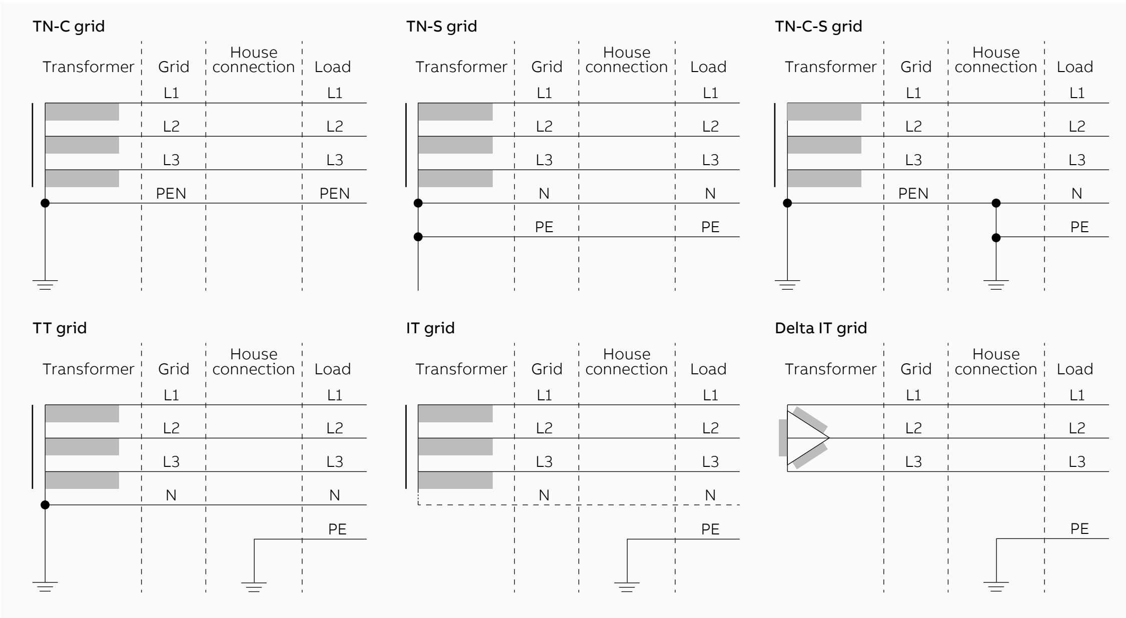


Figure 60
Grid configuration

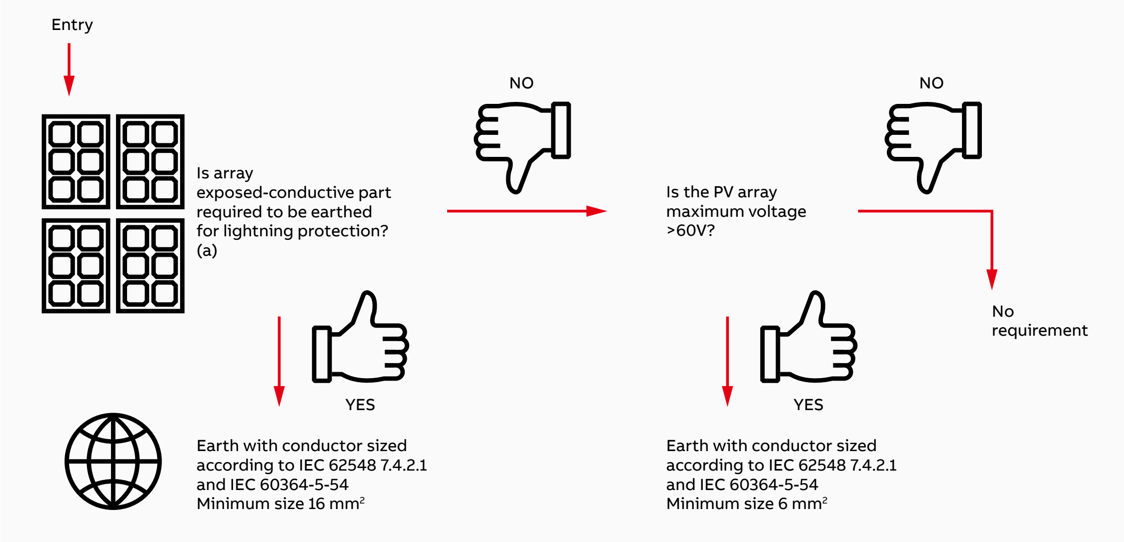
5.2.1 Earthing

The concept of earthing applied to a photovoltaic (PV) system may involve both the exposed conductive parts (e.g. metal frame of the PV modules) as well as the live parts of the PV system (e.g. the cells).

In accordance with IEC 62548, the following options of earthing or bonding of parts of PV arrays could occur:

- Earthing for lighting protection: this kind of earthing will be analysed in paragraph 7;
- Equipotential bonding to avoid uneven potentials across an installation;
- Functional earthing of conductive non-current carrying parts: in this case, earthing or bonding of PV array exposed conductive parts (e.g. metal frame of the panels) shall be performed according to the flow chart requirements (Figure 61); to realize earthing in the field refer to IEC 62305-3.
- Functional earthing of a PV array pole: functionally earthed PV array architectures are described in paragraph 5.2.2.

—
Figure 61
Functional earthing of conductive parts that are non-current carrying decision flow-chart.



A PV system can be earthed only if it is galvanically separated (e.g. by means of a transformer) from the electrical network by means of a transformer. A PV insulated system could seem apparently safer for the people touching a live part; as a matter of fact, the insulation resistance to earth of the live parts is not infinite and then a person may be passed through by a current returning through such resistance. Such current rises as the voltage to earth of the plant and the plant size increase, because the insulation resistance to earth decreases. Besides, the physiological decay of the insulators, due to the passage of time and the presence of humidity, reduces the insulation resistance itself. Consequently, in very large plants, the current flowing through a person touching the live part may cause electrocution and thus the advantage of insulated systems over earthed systems exists only in case of small plants.

5.2.2 Earthing configurations of a PV array architecture

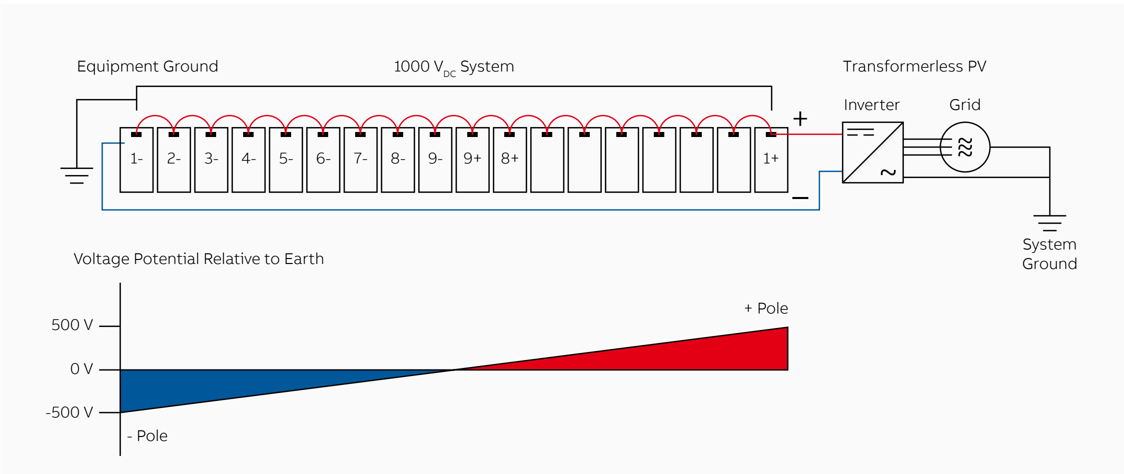
The requirements of PV modules and inverters manufacturers shall be taken into account in determining the earthing system architecture DC side. As mentioned above, a PV system can be earthed only if it is galvanically separated from the electrical network.

5.2.2.1 Unearthed / Ungrounded DC circuits

If the inverter and transformer not provide an insolation or a simple separation from earthed AC system, the unearthed DC circuits are required[25]. PV systems with unearthed DC arrays offer a robust earth fault protection when it is provided with an isolation resistance detection and/or with a residual current monitoring system. In case of failure in any arrays DC cables the earthing of the array is generated in the point of failure and DC arrays switch from floating state to an earth-referenced status. Usually the PV generator is in safety class II[26] and then the first failure not create a closed circuit for fault current.

—
25 According IEC 60364-7-712 functional earthing of a live part on DC side is not allow in case of inverter and transformer that not provide an insolation or a simple separation from earthed AC system.

—
26 According IEC 60364-7-712 PV modules, wiring system used on the DC side shall be class II or equivalent insulation; IEC 60364-7-712 doesn't exclude the use of Safety class I PV modules. Safety class I PV modules are not common.



—
Figure 62
Unearthed / Ungrounded DC circuit

5.2.2.2 High-ohmic earthed / grounded two-wire DC circuits

This kind of earthing system architecture is used in the PV system where a reference voltage to ground is required to prevent PV modules degradation mechanism (e.g. earthing of negative pole of PV arrays is required to prevent potential induced degradation (PID) on crystalline p-type modules). The earthing of the array pole is achieved using an impedance. Impedance value is set to limit fault current (e.g. 300 mA); in case of a hard fault the impedance blown out, the earthed pole is unearthed and the earthing of the array switch in the point of failure: protection system give alarm signal after the resistor blows up. This type of working behaviour reduces the arcing and fire causing currents that can occur with grounded systems. This kind of configuration is allowed only with inverter with integrated transformer: IEC 60364-7-712 requires simple separation or isolation in the inverter or on AC side.
In any case, the compatibility of this configuration with the inverter should be verified with the inverter producer.

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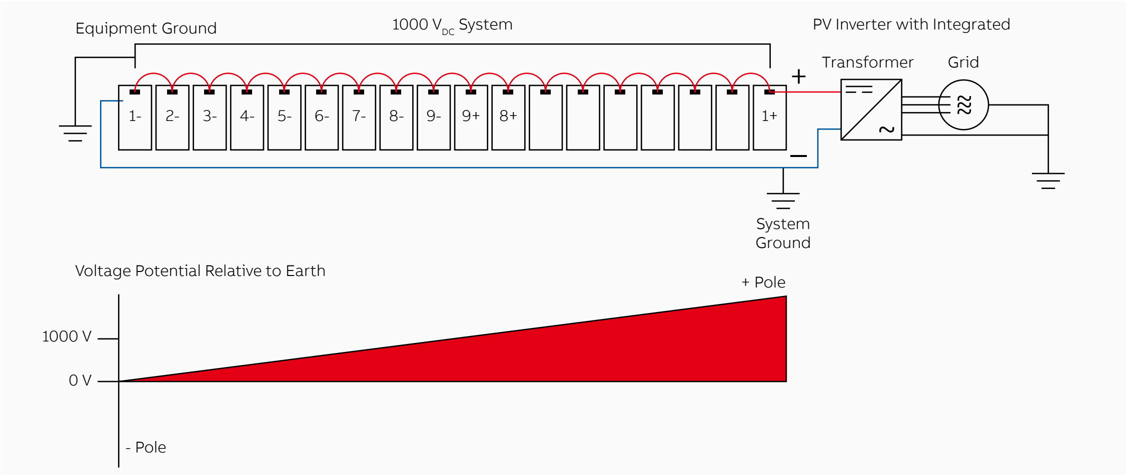
Figure 63
Earthed / grounded two-wire DC circuits (negative pole)



5.2.2.3 Functionally earthed / grounded two-wire DC circuits

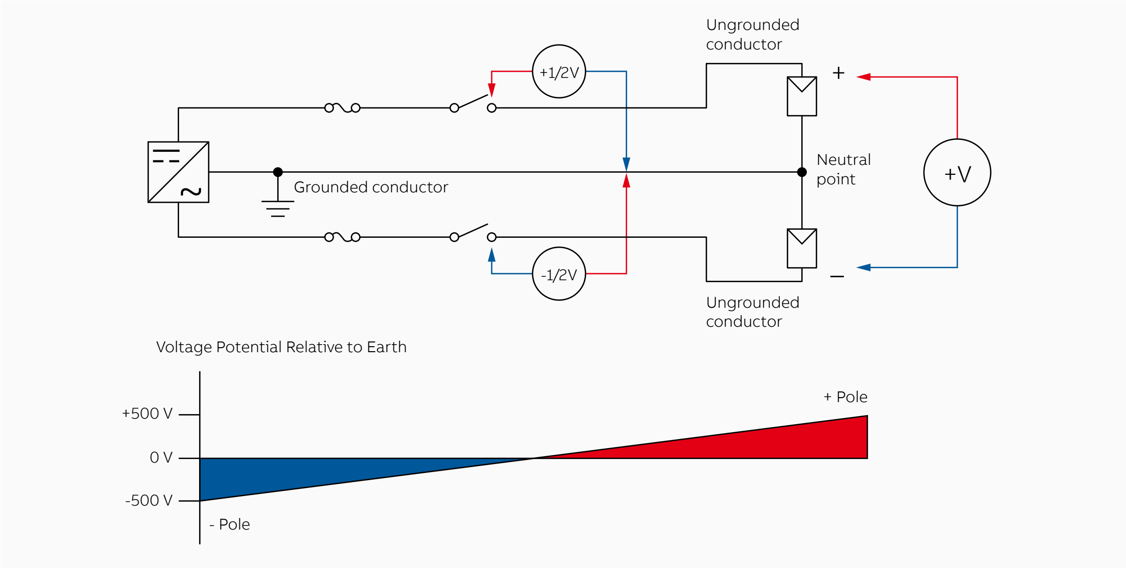
The earthing of one of the conductors of the PV array for functional reasons is allowed through internal connections inherent in the inverter or other earth fault protective device if designed and qualified for this configuration. Functionally earthed DC array is used in the PV system where a reference voltage to ground is required to prevent PV modules degradation mechanism (e.g. earthing of negative pole of PV arrays is required to prevent potential induced degradation (PID) on crystalline p-type modules).
This kind of configuration is allowed only with inverter with integrated transformer: IEC 60364-7-712 requires simple separation or isolation in the inverter or on AC side. In any case, the compatibility of this configuration with the inverter should be verified with the inverter producer.

5.2.2.4 Earthed / grounded bipolar DC circuits

This kind of earthing system architecture is indicated on standard NEC 690.41 and not in the technical specification IEC TS 62738; it is used when:
- inverter require that the reference voltage to ground shall be fixed in the center of the string (center tap);
- the operative voltage of the inverter is greater than the maximum system voltage of the PV modules; with the center tap the reference voltage to ground is fix in the center of the string and then the operative voltage of the PV system could be at least 2 times the maximum system voltage of the module.

The earthing of the center tap is achieved using an impedance or with straight grounding.

—
Figure 64
Earthed / grounded bipolar DC circuits



5.2.3 Protection against the effects of insulation faults

The standard IEC 61215-2 require that, for a PV module, the minimum insulation resistance is 40 MΩ • m²: the area of a 60 monocrystalline 6” cells PV module is around 1,62 m² and then the minimum insulation resistance of this module is around 25 MΩ.
In a PV plant, the insulation resistances of n PV modules connected to the same inverter form a parallel connection against ground and can therefore be added reciprocally:

—
Equation 46

$$R_{iso\ PVplant} = \frac{1}{\frac{1}{R_{iso\ module\ 1}} + \frac{1}{R_{iso\ module\ 2}} + \cdots + \frac{1}{R_{iso\ module\ n}}}$$

If all the n PV modules that compose the PV field are of the same type, the overall resistance of the PV plant against ground could be calculated as follow:

—
Equation 47

$$R_{iso\ PVplant} = \frac{R_{iso\ module}}{n}$$

Where:
n is the number of the modules that compose the PV field.

According to this PV fields with large number of connected PV modules have lower measured insulation resistance values than smaller PV field (e.g. residential system). Higher leakage currents, related to low insulation resistance values, increase the shock hazard risk to personnel.
During the PV field design, the design engineer shall consider the insulation resistance values to define the maximum size of arrays connected to a single inverter DC busbar.
IEC 62548 requires protective measures for DC. insulation faults apply to PV power plant. Depending on earthing configurations of a PV array architecture, the protective measures (detection/measurement, action on fault and indication on fault) shall be properly selected in accordance with IEC 62548.

5.2.4 Plants with Galvanic Isolation - Plants with transformer

PV plants with galvanic insulation of the DC side from the electrical grid can be functionally earthed; the PV generator (DC side) can either be insulated or earthed, as described above in paragraph 5.2.2, as protection against indirect contacts.
Important to differentiate between:

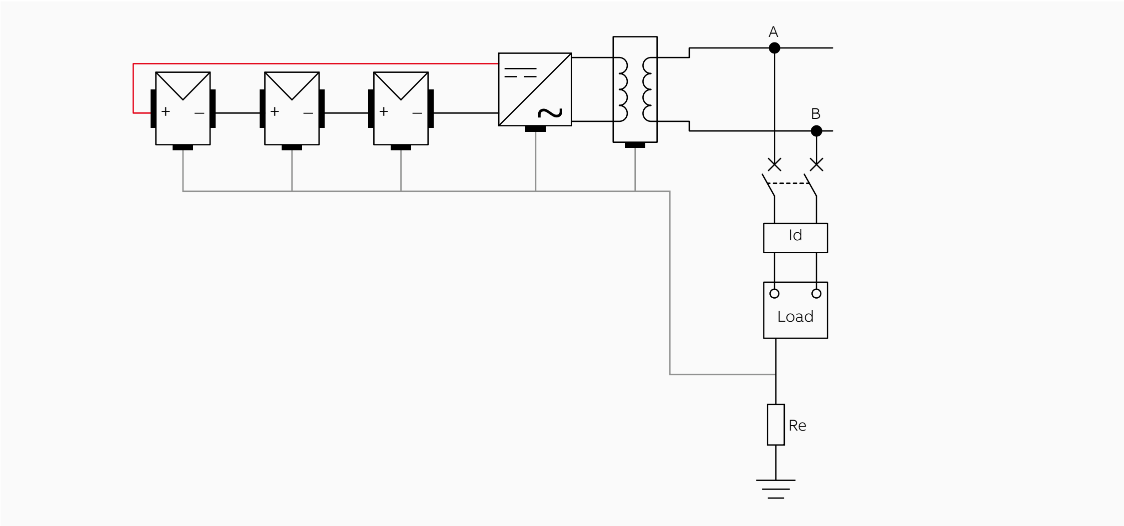
- exposed conductive parts upstream the galvanic isolation point of the installation;
- exposed conductive parts downstream the galvanic isolation point of the installation.

In this case upstream and downstream are referred to the direction of the electric power produced by the PV plant.

5.2.4.1 Exposed conductive parts upstream (PV generator side) the galvanic isolation point of the installation

Plants with an isolated PV generator
In case of plants with an isolated PV generator, live parts of the PV system are insulated and exposed conductive parts (e.g. metal frame of the PV modules) are earthed. The earthing system scheme on DC side is IT.

—
Figure 65
plants with an isolated PV generator, live parts of the PV system are insulated and exposed conductive parts (e.g. metal frame of the PV modules) are earthed



For safety reasons the earthing system of the PV plant results to be in common with the consumer's one. However, to make the insulation controller (Insulation resistance to earth of a PV array) of the inverter operate properly and monitor the PV generator, it is necessary that the frames and/or the supporting structures of the modules (even if of class II) are earthed.

In accordance with IEC 60364-6 the earthing resistance (R_e) of the exposed conductive parts shall meets the following condition:

—
Equation 48

$$R_e \leq \frac{120}{I_d}$$

Where:

- I_d is the current of first fault to earth, which is not known in advance, but which is generally very low in small-sized plants;
- R_e is the earthing resistance of the consumer plant, which is defined for a fault in the network.

In the case of double faults, in accordance with IEC 60364-6, the voltage of interconnected exposed conductive parts will be lower than:

—
Equation 49

$$I_{sc} \cdot R_{eqp} \leq 120V$$

Where:
- I_{sc} is the current of the involved modules at short circuit;
- R_{eqp} is the resistance of the conductor interconnecting exposed conductive parts affected by the fault.

For instance, if R_{eqp} = 1Ω (value approximated by excess) then Isc not exceeding 120 A which is usual in small-sized plants; therefore, the effective touch voltage in case of a second earth fault does not result hazardous.
On the contrary, in large-sized plants it is necessary to reduce to acceptable limits the chance that a second earth fault occurs, by eliminating the first earth fault detected by an insulation resistance surveillance controller (either inside the inverter in accordance with IEC 62109-2 or external).

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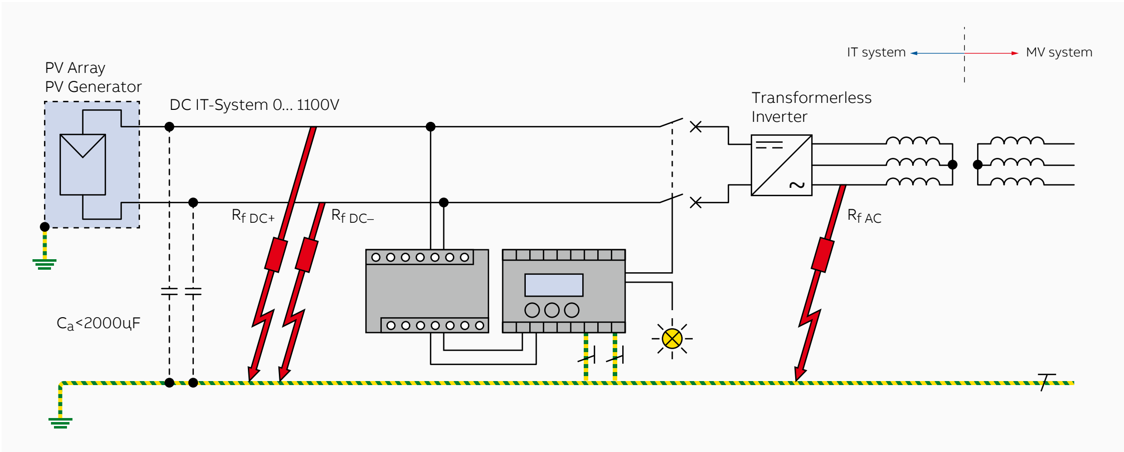
Figure 66
insulation surveillance controller



In accordance with IEC 62548, a means shall be provided to measure the insulation resistance from the PV array to earth:
- immediately before the operation starting;
- and at least once every 24 h.

Measure the insulation resistance from the PV array to earth can be done by:
- an insulation measuring device in accordance with IEC 61557-2;
- or an insulation monitoring device (IMD) in accordance with IEC 61557-8.

Minimum threshold values for detection depends from the PV field dimension (ref. Table 1 – IEC 62548)

—
Table 1

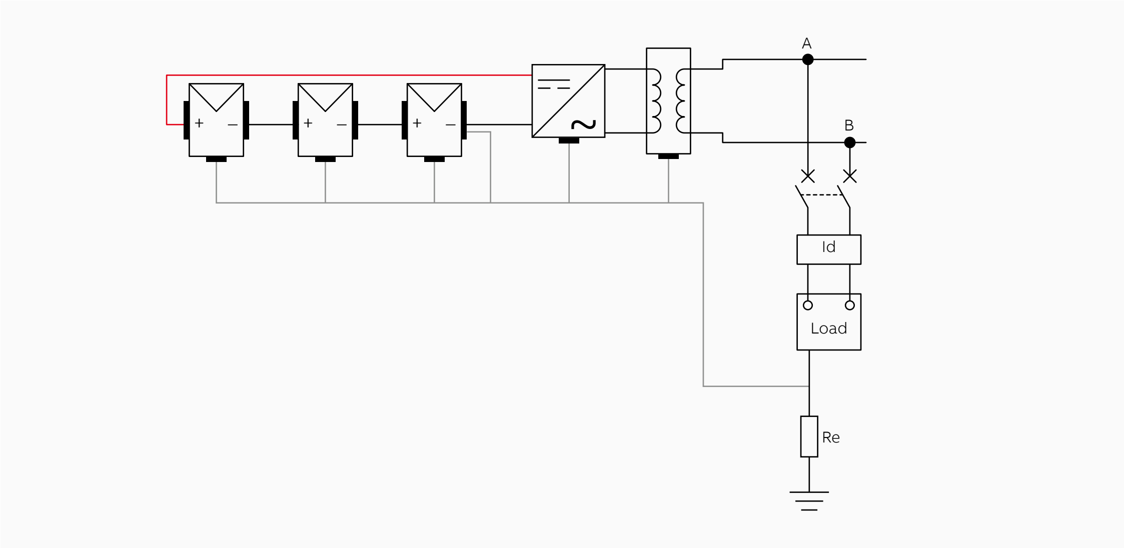
PV field dimension [kW]	R_{iso} limit [kΩ]
PV field dimension <20 kW	30
20 kW< PV field dimension<30 kW	20
30 kW< PV field dimension<50 kW	15
50 kW< PV field dimension<100 kW	10
100 kW< PV field dimension<200 kW	7
200 kW< PV field dimension<400 kW	4
400 kW< PV field dimension<500 kW	2
PV field dimension >500 kW	1

In all cases of insulation fault, the R_{iso} measurements may continue, the fault indication may stop and the system may resume normal operation only in case R_{iso} has recovered to a value higher than the limit indicated in Table 1.

— 27 In case of high voltage system (>1000 V) on DC side, it is recommendable to use Unearthed / Ungrounded DC circuits.

Plant with a functionally earthed PV generator

In case of plants with a functionally earthed PV generator, live parts of the PV system and exposed conductive parts (e.g. metal frame of the PV modules) are earthed.
The earthing system scheme on DC side is TN[27].



— Figure 67 plants with a functionally earthed PV generator, live parts of the PV system and exposed conductive parts (e.g. metal frame of the PV modules) are earthed

In the presence of an earth fault, a short-circuit occurs as in the usual TN systems, but such current cannot be detected by the maximum current devices since the characteristic of the PV plants is the generation of fault currents with values not much higher than the rated current. Due to this difference between PV plants' fault currents and the rated current, large PV plants operating at voltage around 1000V will become high risk plants.
In accordance with IEC 62548, a means shall be provided to monitor the PV earth fault current by:
- residual current monitoring system;
- earth fault interrupting means.

The residual current monitoring shall be provided whenever the PV array is connected to an earth reference with the automatic disconnection means closed. It shall measure the total (AC and DC components) RMS residual current. The residual current monitoring, in case of fault, shall cause action on fault within 0,3 s and indicate the fault the continuous residual current exceeds the limit value.
The limit value, in accordance with IEC 62548, is:
- 300 mA for inverters with output power rating ≤ 30 kVA;
- 10 mA per kVA of rated output power (in any case at least 5 A) for inverters with output power rating > 30 kVA.

The action on fault could be the disconnection of:
- the output circuit from any earthed output circuit; or
- the PV array; or
- all poles of the faulty part of the PV array from the inverter.

This residual current functionality can be provided by inverter (in accordance with IEC 62109-2).

The earth fault interrupting mean could be achieved by a device that automatically interrupt the current in the functional earthing conductor in case of earth fault on the DC side. The device shall be rated for the maximum voltage of the PV array and shall have a rated breaking capacity equal to the maximum short-circuit current of the PV array. The device that allow to interrupt the earth fault shall have a rated current not exceeding the values indicated in Table 2 (IEC 62548)

— Table 2

PV field dimension [kW]	R_{iso} limit [kΩ]
PV field dimension <25 kW	1
25 kW< PV field dimension<50 kW	2
50 kW< PV field dimension<100 kW	3
100 kW< PV field dimension<250 kW	4
PV field dimension >250 kW	5

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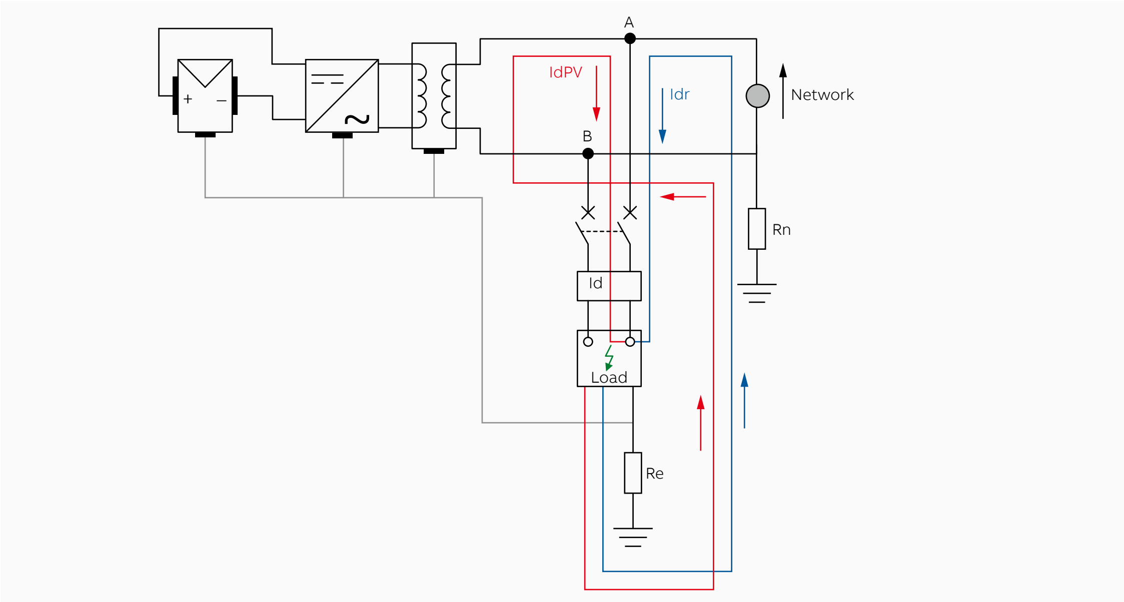
5.2.4.2 Exposed conductive parts downstream (load side) the galvanic isolation point of the installation

The installation of a PV plant on the AC side is generally protected through automatic disconnection of supply that can be established through protective electric bonding combined with a miniature circuit-breaker or a residual-current device in accordance with IEC 60364-4-41.

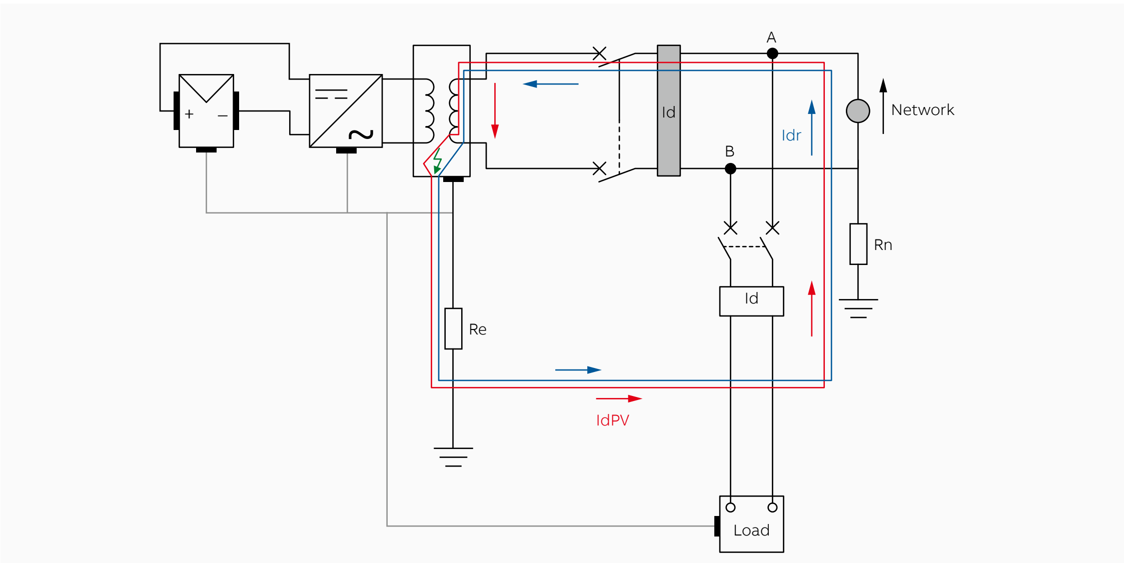
Network-consumer with TT grounding system and exposed conductive parts belonging to the consumer's plant
In a network-consumer with TT grounding system a residual current circuit-breaker is required as primary fault protection. The residual current circuit-breaker positioned at the beginning of the consumer's plant protect the exposed conductive parts belonging to the consumer's plant against the faults supplied by both the network as well as by the PV generator.

—
Figure 68
network-consumer system of TT type protected by a residual current circuit-breaker positioned at the beginning of the consumer's plant; the exposed conductive parts belonging to the consumer's plant.



Network-consumer with TT grounding system and exposed conductive parts between the parallel point A-B and the network
In a network-consumer with TT grounding system a residual current circuit-breaker is required as primary fault protection. The residual current circuit-breaker positioned at the beginning of the consumer's plant fails in case of exposed conductive parts between the parallel point A-B and the network.
A residual current protection device shall specifically be installed to protect exposed conductive parts between the transformer's secondary and the circuit-breakers.

—
Figure 69
network-consumer system of TT type protected by a residual current circuit-breaker positioned at the beginning of the consumer's plant and by a residual current circuit-breaker positioned between the transformer's secondary and the circuit-breakers; the exposed conductive parts between the parallel point A-B and the network.



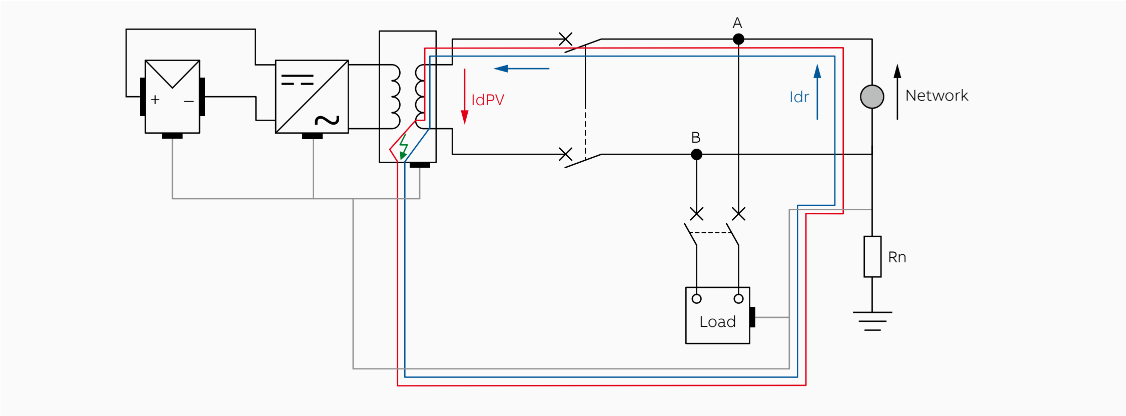
Network-consumer with TN grounding system and exposed conductive parts between the parallel point A-B and the network

In a network-consumer with TN grounding system the residual currents are much higher than the rated residual current of the residual-current device. The fault current on the AC side causes the tripping of the overcurrent devices (miniature circuit-breaker) by the times prescribed in the Standard. In case of exposed conductive parts between the parallel point A-B and the network, residual current circuit-breakers are not needed; the overcurrent devices (miniature circuit-breaker) can guarantee protection through automatic disconnection if the rated residual current is coordinated with the earth resistance R_e, in compliance with the usual relation of TT systems:

Equation 50

$$R_e \leq \frac{50}{I_d}$$

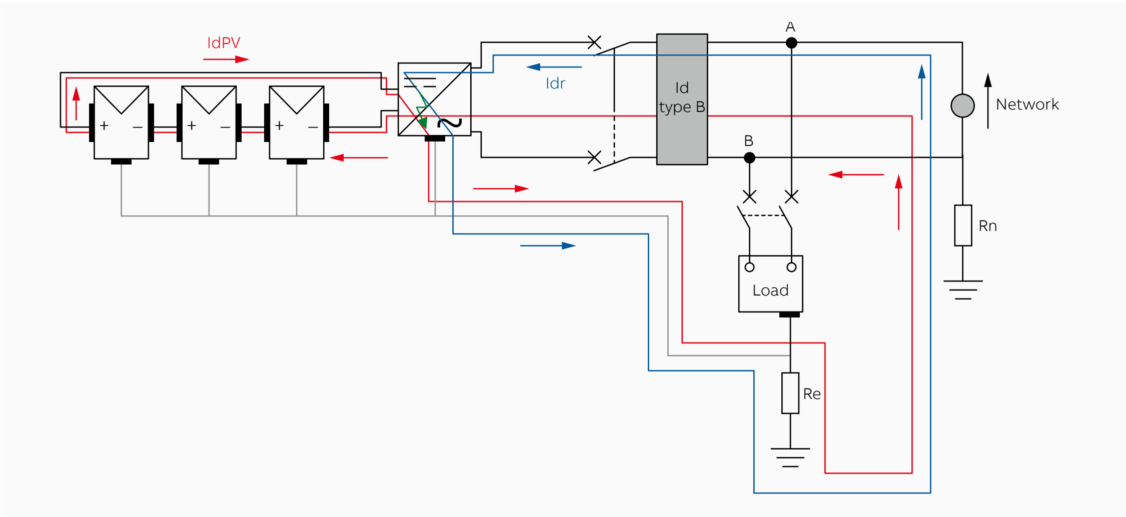
Figure 70
network-consumer system of TN type; the exposed conductive parts between the parallel point A-B and the network.



5.2.5 Plants without Galvanic Isolation - Plants without transformer

In case of absence of the separation transformer between the PV installation and the network, the PV installation itself shall be insulated from earth in its active parts and becomes an extension of the supply network, generally with a point connected to earth (TT or TN system). As regards the exposed conductive parts of the consumer's plant and upstream the parallel point A-B, from a conceptual point of view, what described in paragraph 5.2.4.2 is still valid. On the DC side, an earth fault on the exposed conductive parts determines the tripping of the residual current circuit-breaker positioned downstream the inverter. After the tripping of the residual current device, the inverter goes in stand-by due to the lack of network voltage, but the fault is supplied by the PV generator.

Figure 71
plants with an isolated PV generator, and an inverter transformer-less



Since the PV system is type IT in DC side, the considerations made in paragraph 5.2.4.1, for plants with an isolated PV generator, are still valid. For earth faults on the DC side and on the exposed conductive parts upstream the parallel point A-B, the residual current circuit-breaker on the load side of the inverter is passed through by a residual current which is not alternating. Where a residual current device (RCD) is used for protection of the PV AC supply circuit, according to the requirements of IEC 60364-7-712, the RCD shall be of type B in accordance with IEC 62423 or IEC 60947-2.

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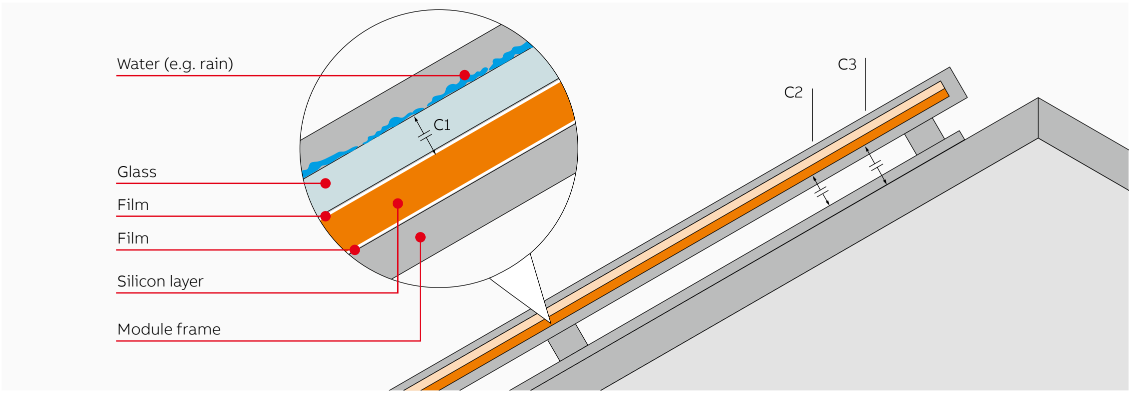
5.2.6 Capacitive Leakage Current

The mechanical structure of the modules and their installation generate a "parasitic" capacitance. The parasitic capacitance is proportional to the conductive surfaces present in the PV array. The parasitic capacitance will increase even further if the surfaces are damp (e.g. from rain, condensation). Parasitic capacitance does not affect the PV modules insulation, so personal safety is still guaranteed but the PV inverter working behaviour could be conditioned.
The PV modules installed on a roof cause 3 different type of Parasitic Capacitance:

- C1 Parasitic capacitance due to film of water on the glass;
- C2 Parasitic capacitance due to grounded support frame;
- C3 Parasitic capacitance due to roof surface area.

—
Figure 72
parasitic capacitances



The total parasitic capacitance is:

—
Equation 51

$$C_{TOT} = C1 + C2 + C3$$

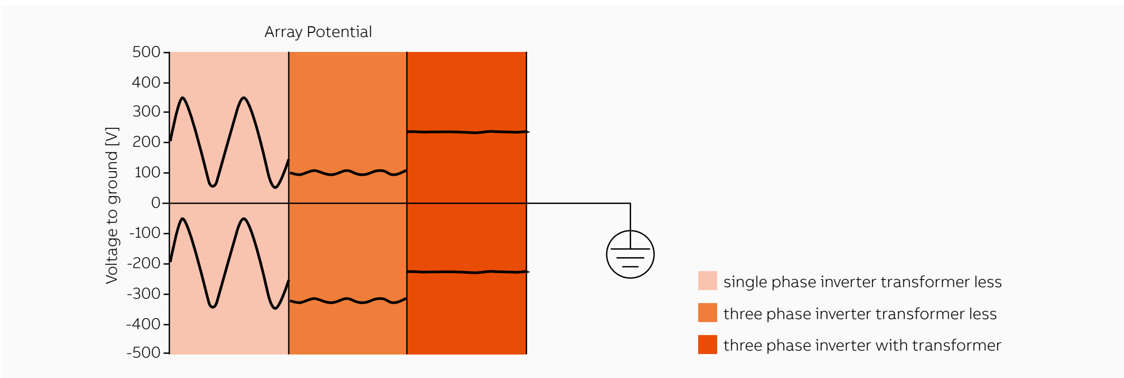
Usually the overall capacitance C_{TOT} is dominated by C1 in rainy and wet conditions and then C2 and C3 can be neglected.

—
Equation 52

$$C3 \ll C2 \ll C1$$

During operation the inverter connect the PV modules to the AC. Depending on the inverter type, a part of the alternating voltage amplitude arrives at the PV module and then complete PV array oscillates with an alternating voltage in relation to its environment.
Using single-phase transformer-less inverters, usually half of the grid amplitude is passed on to the PV module. Using three-phases transformer-less inverters, the oscillations amplitude is smaller than single-phase transformer-less inverters. Using inverters with transformers, a small "ripple" of just a few volts could be detected.

—
Figure 73
array potential



This fluctuating voltage constantly changes the status of charge of the parasitic capacitor and a capacitive leakage current, proportional to the capacitance and the applied voltage amplitude, is generated. If a fault (e.g. defective insulation) causes a live line to come into contact with a grounded person an additional current flow to ground. The total currents (leakage current and residual current) is the differential current. In order to provide personal safety, in case a residual current of 30 mA occurs, the transformer-less inverters must be disconnected from the utility grid and then, for this purpose, during feed-in operation, the differential current (leakage current + residual current) is measured using an all-pole sensitive residual-current monitoring unit.

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Protection against overcurrent

Protection against overcurrent

6.1 Protection against overcurrent on DC side

6.1.1 Cable protections

It is not necessary to protect PV string cables against overloads if they are chosen with a current carrying capacity equal to or greater than 1.25 times the I_{sc}.

Equation 53

$$I_{cu\,string} \geq 1.25 \cdot I_{sc}$$

It is not necessary to protect PV sub-array cables against overloads if they are chosen with a current carrying capacity equal to or greater than 1.25 times the sum of the I_{sc} of the sub-array strings.

Equation 54

$$I_{cu\,sub-array} \geq 1.25 \cdot S_{SA} \cdot I_{sc}$$

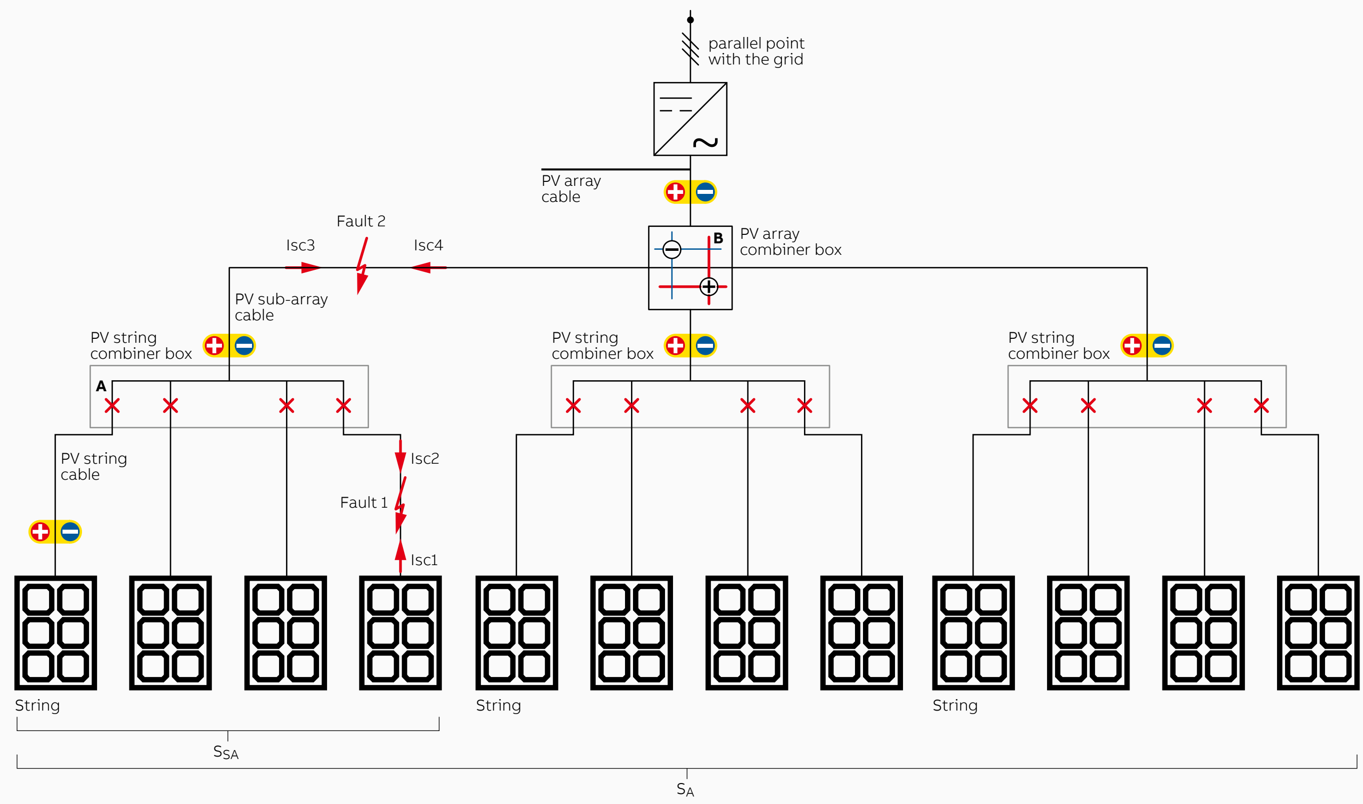
where:
S_{SA} is the number of parallel-connected PV strings in the PV sub-array.

It is not necessary to protect the PV array cables against overloads if they are chosen with a current carrying capacity equal to or greater than 1.25 times the sum of the I_{sc} of the array strings.

Equation 55

$$I_{cu\,array} \geq 1.25 \cdot S_A \cdot I_{sc}$$

where:
S_A is the number of parallel-connected PV strings in the PV array.
(see draw on next page)



—
Figure 74
array, sub-array and strings cables faults

- **A** represents the protective device installed in the PV string combiner box.
- **B** represents the protective device installed in the PV array combiner box.
- S_{SA} is the number of parallel-connected PV strings in the PV sub-array.
- S_A is the total number of parallel-connected PV strings in the PV sub-array.

Regarding short-circuit, overcurrent within a PV array could occur on the DC cables of PV generator in case of:
- fault between the polarity of the PV system (short circuits in PV generator components);
- fault to earth in the earthed systems;
- double fault to earth in the earth-insulated systems.

PV modules are current limited sources and their short-circuit current (I_{sc}) value is just higher than the operative current (I_{MPP}).
In case of short-circuit affect the string cables or connectors (Fault 1 in the Figure 74), the string cable is supplied:
- upstream by the string under consideration (I_{SC1}= 1.25 · I_{sc});
- downstream by the other (S_A - 1) strings connected (I_{SC2}= 1.25 · (S_A-1)·I_{sc}).

In case of a small-sized PV plant with 2 strings only (S_A= 2), it results that:

—
Equation 56

$$I_{SC2} = 1.25 \cdot (2-1) \cdot I_{sc} = I_{SC1}$$

Therefore, it is not necessary to protect the PV string cables and connectors against short-circuit.
In case the strings connected in parallel are more than 3 (S_A≥3), it results that:

—
Equation 57

$$I_{SC2} > I_{SC1}$$

Therefore, the cables and the string connectors must be protected against the short-circuit when their current carrying capacity is lower than I_{sc2}.

—
Equation 58

$$1.25 \cdot I_{sc} \leq I_{z\ string} < I_{SC2} = 1.25 \cdot (S_A - 1) \cdot I_{sc}$$

In case of short-circuit affect the cables between a PV string combiner box and the PV array combiner box (Fault 2 in the Figure 74), the string cable is supplied:
- upstream by the PV sub-array string ($I_{SC3} = 1.25 \cdot S_{SA} \cdot I_{sc}$);
- downstream by the other (S_A - S_{SA}) strings connected ($I_{SC4} = 1.25 \cdot (S_A - S_{SA}) \cdot I_{sc}$).

In case of a PV plant where $S_A = 2\ S_{SA}$), it results that:

Equation 59

$$I_{SC4} = 1.25 \cdot (2S_A - S_A) \cdot I_{sc} = 1.25 \cdot S_A \cdot I_{sc} = I_{SC3}$$

Therefore, it is not necessary to protect the PV sub-array cables against short-circuit.
In case the $S_A > 2\ S_{SA}$, it results that:

Equation 60

$$I_{SC4} > I_{SC3}$$

Therefore, the cables must be protected against the short-circuit when their current carrying capacity is lower than I_{sc4}.

Equation 61

$$1.25 \cdot S_{SA} \cdot I_{sc} \leq I_{z\ sub-array} < I_{SC4} = 1.25 \cdot (S_A - S_{SA}) \cdot I_{sc}$$

6.1.2 Protection of strings against reverse current

Due to shading or faults a string could become passive and then absorb and dissipate the electric power generated by the other strings connected in parallel; a current which flows through the string under consideration in reverse direction with respect to that of standard operation conditions; the reverse current could damages the modules ($I_{rev\ module}$ is the maximum reverse current that the PV modules allow; it is indicated in the PV modules datasheet).
In case of S_A strings connected in parallel, the highest reverse current ($I_{rev\ max}$) is equal to:

Equation 62

$$I_{rev\ max} = (S_A - 1) \cdot I_{sc}$$

If $I_{rev\ max} < I_{rev\ module}$ the protection of strings against reverse current is not necessary.
Otherwise, if $I_{rev\ max} > I_{rev\ module}$ the protection of strings against reverse current is strictly necessary in accordance with IEC 62548 clause 6.5.3.

6.1.3 Contribution of the inverter

The contribution to short-circuit on the DC side of the inverter may come from the grid and from the discharge of the capacitors inside the inverter. The grid short-circuit current is due to the free-wheeling diodes of the inverter which in this case acts as a bridge rectifier. Such current is limited by the impedances of the transformer and of the inductors belonging to the output circuit.
In case of inverter with galvanic insulation at 50 Hz, this current exists.
In case of inverter without galvanic insulation (transformer-less inverters), usually it has a DC/DC converter in input; so that the operation of the PV generator on a wide voltage range is guaranteed; if the DC/DC converter is boost converter, due to its constructive typology, includes at least one blocking diode which prevents the grid current from contributing to the short-circuit; if the DC/DC converter is buck converter, due to its constructive typology, it is not able to prevent the grid current from contributing to the short-circuit.
The discharge current of the capacitors is limited by the cables between inverter and fault and exhausts itself with exponential trend: the lowest the impedance of the cable stretch, the highest the initial current, but the lowest the time constant of the discharge. The energy which flows is limited to that one initially stored in the capacitors.
In case of blocking diode installed in series with one of the two poles, the contribution to short-circuit is null.
In case of a very high discharge current of the capacitors, associated to long time constants, an increase in the breaking capacity of the circuit-breakers could be required.

6.1.4 Choice of protective devices

As regards the protection against the short-circuits on the DC side, in accordance with IEC 62548 clause 7.3, the devices shall:

- be obviously suitable for DC usage;
- have a rated service voltage equal or higher than the PV string/array maximum voltage (cf. paragraph 3.2.2);
- have an IP rating suitable for the installation location and environment;
- have a temperature rating appropriate to the installation location and application.

Where string overcurrent protection is required, one of the following options could be chose:

a) each PV string shall be protected with an overcurrent protection device, where the nominal overcurrent protection rating of the string overcurrent protection device shall be I_n where:

Equation 63

$$1.5 \cdot I_{sc} < I_n < 2.4 \cdot I_{sc}$$

Equation 64

$$I_n < I_{rev\ module}$$

where:

$I_{rev\ module}$ is the maximum reverse current that the PV modules allow; it is indicated in the PV modules datasheet.

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

Equation 65

$$1.5 \cdot S_g \cdot I_{sc} < I_{n\ g} < \{I_{rev\ modue} - [(S_g - 1) \cdot I_{sc}]\}$$

where:

S_g is the number of strings in a group under the protection of the one overcurrent device;

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

Strings can generally be grouped only under one overcurrent protection device if the maximum reverse current that the PV modules allow ($I_{rev\ module}$) is greater than 4 times I_{sc}.

In order to protect the string cables, the connectors and PV modules against overcurrent and/or reverse current, the following standard methods can be applied to the strings:

- gPV fuses, in accordance with the IEC 60269-6 standard, connected in series to the individual string; despite the easy usage of fuses, attention must be paid to the sizing and choice of such devices, which shall not only have rated current given by the previous formulas, but also tripping characteristic type gPV (IEC 60269-6), shall be inserted into suitable fuse holders and be able to dissipate the power generated under the worst operating conditions. In accordance with IEC 60364-7-712 both polarities shall be protected[28].
- string diode connected in series with the individual string: it can prevent any reverse current in the protected string. In case of diode failure, it may cause the loss of the safety function and/or involve the string failure. Moreover, the string current flows always through the diode connected in series and the string diode generate continuous losses.Blocking diodes are not common in a grid connect system because their function is better served by the installation of a string fuse. By the way, for multi-string arrays with thin-film PV modules, provide adequate overcurrent / reverse current protection with string fuses or MCB (miniature circuit-breaker) couldn't be possible (it may not be possible to specify a fuse / MCB which is greater than 1.25 times the I_{sc} x 1.25 and at the same time smaller than the reverse current rating of the module). In this situation blocking diodes[29] should be used in addition to string fuses.

(see next page)

28 IEC 62548 clause 6.5.7 considers an exception in case of not functionally earthed systems provided with only two active conductors: in case a segregation between string cables and sub-array cables is available or in case there are no sub-arrays, an overcurrent protective device could be placed in one unearthed live conductor of the string cable or sub-array cable.

29 Local country requirements shall be taken into account for the use of blocking diodes. In some countries, blocking diodes are not considered reliable enough to replace overcurrent protection (ref. IEC 62548 clause 7.3.12).

6

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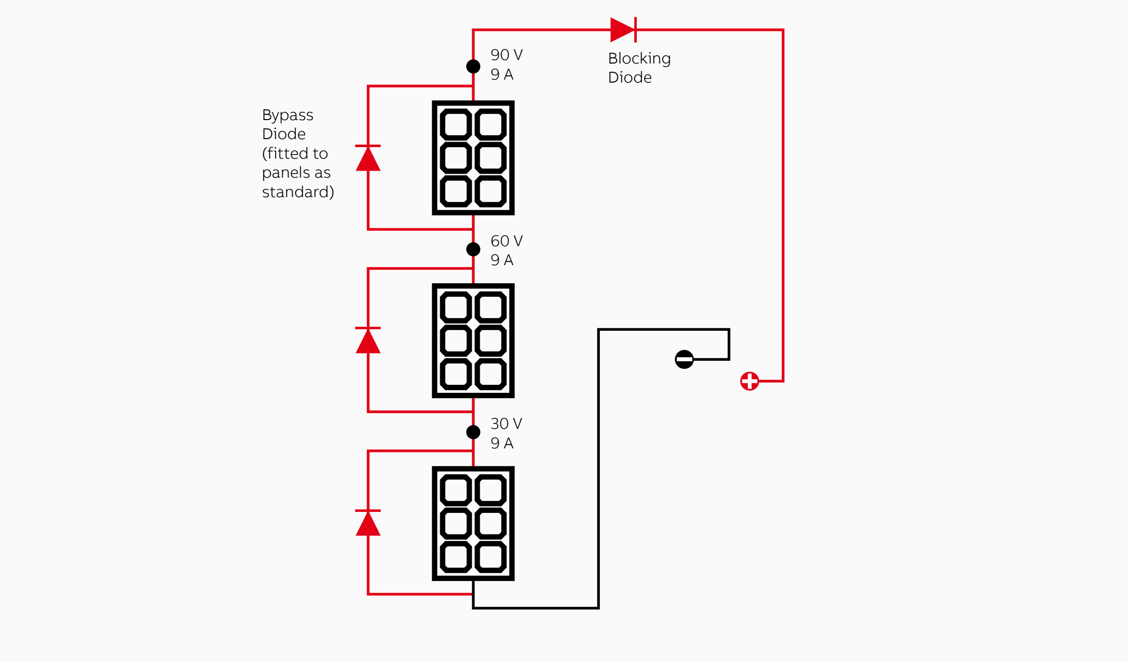
Figure 75
blocking diode
installation



The blocking diode must have:

- A reverse voltage rating > 2 times the maximum system voltage;
- A current rating > 1.4 times the I_{sc} (where I_{sc} is the relevant short-circuit current for the string / sub array / array);
- An adequate cooling.

- MCB - miniature circuit-breaker (thermomagnetic circuit-breakers) with overcurrent protection elements (in accordance with IEC 60898-2): it shall meet the string fuse criteria and it shall be rated for use in an inductive circuit and allow DC currents flowing in either direction through the device. When miniature circuit-breaker with overcurrent protection elements is used, it may also provide the disconnecting means to isolate both polarity[30] of the PV array from the power conversion equipment and vice versa and to allow for maintenance and inspection tasks to be carried out safely. The miniature circuit-breaker with overcurrent protection elements are designed to be used at a defined ambient temperature: in case of overtemperature in the combiner box, the miniature circuit-breaker with overcurrent protection elements is derated; the maximum operation temperature should be verified in advance during the design of the miniature circuit-breaker to avoid unexpected triggering.

—
30
IEC 62548 clause 6.5.7 considers an exception in case of not functionally earthed systems provided with only two active conductors: in case a segregation between string cables and sub-array cables is available or in case there are no sub-arrays, an overcurrent protective device could be placed in one unearthed live conductor of the string cable or sub-array cable.

In order to protect sub-array cables against overcurrent and/or reverse current usually gPV fuses, in accordance with the IEC 60269-6 standard, connected in series to the sub-array cables could be used. Also MCB (Miniature Circuit-Breakers) or MCCB (Molded Case Circuit-Breaker) connected in series to the sub-array cables could be used.
The nominal rated current (In) of overcurrent protection devices for PV sub-arrays shall be determined with the following formula:

—
Equation 66

$$1.25 \cdot S_{SA} \cdot I_{sc} < I_n < \ 2.4 \cdot S_{SA} \cdot I_{sc}$$

The 1.25 multiplier used here instead of the 1.5 multiplier used for strings is to allow designer flexibility.

In order to protect all the connection cables the protective device must be chosen so that the following relation is satisfied for each value of short-circuit (IEC 60364) up to a maximum prospective short-circuit current:

—
Equation 67

$$I^2 \cdot t \leq K^2 \cdot S^2$$

Where:
$I^2 \cdot t$ is the Joule integral for the short-circuit duration (in A^2s);
K is a characteristic constant of the cable, depending on the type of conductor and isolating material;
S is the cross-sectional area of the cable (in mm^2).
In case of each PV string is protected with an overcurrent protection device, the rated ultimate short-circuit breaking capacity, of the devices in the PV string combiner box, must be not lower than the short-circuit current of the other (S_A-1) strings:

Equation 68

$$I_{cu} \geq 1.25 \cdot (S_A - 1) \cdot I_{sc}$$

In case of strings grouped in parallel under one overcurrent device protection, the rated ultimate short-circuit breaking capacity, of the devices in the PV string combiner box, must be not lower than the short-circuit current of the other (S_A- S_g) strings:

Equation 69

$$I_{cu} \geq 1.25 \cdot (S_A - S_g) \cdot I_{sc}$$

The devices in the PV array combiner box must protect against short-circuit the sub-array cables when these cables have a current carrying capacity lower than (c.f. Figure 74):

Equation 70

$$I_{SC4} = 1.25 \cdot (S_A - S_{SA}) \cdot I_{sc}$$

In such case, these devices shall satisfy the following relation:

Equation 71

$$1.25 \cdot S_{SA} \cdot I_{sc} < I_n < 2.4 \cdot S_{SA} \cdot I_{sc}$$

while their rated ultimate short-circuit breaking capacity shall not be lower than the short-circuit current of the other (S_A- S_{SA}) strings, that is:

Equation 72

$$I_{cu} \geq 1.25 \cdot (S_A - S_{SA}) \cdot I_{sc}$$

6.1.5 Positioning of overcurrent protection devices

Overcurrent protection devices shall be placed (IEC 62548):
- for string overcurrent protection devices, they shall be where the string cables join the sub-array or array cables in the string combiner box;
- for sub-array overcurrent protection devices, they shall be where the sub-array cables join the array cables in the array combiner box;
- for array overcurrent protection devices, they shall be where the array cables join the power conversion equipment.

The location of the overcurrent protection devices at the end of those cables which are furthest away from the PV sub-array or string is to protect the system and wiring from fault currents flowing from other sections of the PV array or from other sources such as batteries.

6.2 Protection against overcurrent on AC side

Since the cable connecting the inverter to the point of parallel with the grid shall be dimensioned to obtain a current carrying capacity higher than the maximum current which the inverter can deliver, a protection against overload is not needed. However, the cable must be protected against a short-circuit supplied by the grid through a protective device positioned near the point of parallel with the grid.
To protect such cable, the main circuit-breaker of the consumer plant can be used if the specific let-through energy is withstood by the cable. However, the trip of the main circuit-breaker put all the consumer plant out of service. According to this, even if a dedicated protection against overload is not needed, and also if the main circuit-breaker of the consumer plant is not close to the inverter, it is advisable to position the protection device in order to also avoid the main circuit-breaker of the consumer plant triggering; this circuit-breakers shall be selective with the main circuit-breaker of the consumer plant. In case of utility scale PV power plant, there is not a consumer plant. According to this scenario, only a main circuit-breaker of the complete PV Pant shall be available. In multi-inverter plants, the presence of one protection for each inverter line ensures, in case of fault on an inverter, the functioning of the other ones, provided that the circuit-breakers on each line are selective with the main circuit-breaker of the consumer plant.

6

6.3 Choice of switching and disconnecting devices

The installation of a disconnecting device on each string is recommended to allow verification or maintenance interventions on the string without putting out of service other parts of the PV plant.
The disconnection of the inverter must be possible both on the DC side as well as on the AC side so that maintenance is allowed by excluding both the supply sources (grid and PV generator) (IEC 60364-7).
On the DC side of the inverter a disconnecting device shall be installed which can be switched under load, such as a switch-disconnector.
On the AC side a general disconnecting device[31] shall be provided. The protective device installed at the connection point with the grid can be used; if this device is not close to the inverter, it is advisable to install a disconnecting device immediately on the load side of the inverter.

—
31
If a LV circuit-breaker is used, it has usually also the capability of insolation.

Protection against overvoltage

Protection against overvoltage

7.1 Selection of surge protective devices (SPD) for the protection of PV plants against lightning

Lightning events are one of the threats of electrical installations. The atmospheric discharges during a lightning storm can reach up to hundreds of kiloamperes. Nowadays, despite technological improvements, no devices are designed to prevent lightning formation. However, Lightning Protection Systems (LPS) are designed to minimize damage to the surrounding environment.
Damage to electrical installations could come from:

- direct strike – direct overvoltage;
- indirect strike - induced overvoltage.

According to the current state of scientific knowledge, PV modules do not increase the risk of a lightning strike and then the PV modules installation could not be a driver for lightning protection measures installation.
Where protection against transient overvoltage is required by IEC 60364-4-44 clause 443, such protection shall also be applied to the DC side of the PV installation. Further protection against transient overvoltage may be required on the AC side depending on the distance between the inverter and the origin of the installation.
In case IEC 60364 4-44 clause 443 does not require protection against transient overvoltage of atmospheric origin, a risk assessment shall be performed.
The risk assessment normally, for large scale PV system, could be performed in accordance with the IEC 62305-2 “Protection against lightning - Part 2: Risk management”; this standard shows that the risk of human losses is always lower than the tolerable risk, above all due to the limited presence of human beings, whereas, in such structure, there is always the risk of economic losses connected not only to the value of the plant components which could be damaged, but also, above all, to a possible stop of production.
When the cost for losses exceeds that of the protection measures, a protection system becomes necessary; this is very likely, when considering the high economic impact of production downtime. However, let it be clearly understood that only the owner or the manager of the plant can define the tolerable damage frequency F_T. This definition cannot leave the above mentioned economic evaluations out. As an indication, a typical range of values is: from one damage over a period of 20 years ($F_T = 0.05$) to one damage in 10 years ($F_T = 0.1$). Once the value of the damage frequency has been defined and determined, it is possible, in compliance with the IEC 62305-2, to select and define the size of the protection measures.
In case of small PV system, the risk assessment could be performed:

- for AC side in accordance with IEC 60364-4-44 clause 443;
- for DC side in accordance with IEC 60364-7-712 clause 712.443.5.101; it provides that the risk assessment may be carried out to evaluate if protection against transient overvoltage is required in case the relevant data is available. SPDs shall be installed on the DC side of the installation where the maximum route length (L) between the inverter and the connection points of the photovoltaic modules of the different strings is equal to or longer than the critical length (L_{crit}).

—
Equation 73

$$L \geq L_{crit}$$

L_{crit} depends on the type of PV installation, and is calculated according to the following table.

Table 3

Type of installation	PV installation is attached to the building	PV installation is not attached to the building
L_{crit} [m]	115 / N_g	200 / N_g
$L \geq L_{crit}$ [m]	Surge protection is required on DC side	

Where:
N_g is the lightning ground flash density (flash/km²/year) relevant to the location to the power line and connected structures. This value may be determined from ground flash location networks in many areas of the world.
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") and IEC 60364-7-712 provide information on selecting and implementing surge protective devices in PV power supply systems.
In the selection and defining of the protection measures, a distinction shall be made between the PV plants installed on roofs and those ones on ground; IEC 61643-32 describe three different applications for PV installations in Buildings with PV systems:
- without external Lightning Protection System (LPS);
- with external LPS and sufficient separation distance;
- with external LPS, without enough separation distance.

7.1.1 PV plants on roofs

In case of PV plants on roofs, the first thing to do is to calculate the collection area of the building to establish, in compliance with the IEC 62305-2, whether there is the need to install a Lightning Protection System (LPS). The LPS consists of the protective systems, both external (detectors, lightning conductors and ground electrodes) as well as internal (protective measures to reduce the electromagnetic effects of the lightning currents entering the structure to be protected).

7

7.1.1.1 PV installations in Buildings with PV systems without external Lightning Protection System (LPS)

Even if the installation of an LPS is not required and then no external lightning protection system is installed, surge protective devices should be installed in accordance with IEC 61643-32.

Equipotential bonding

Minimum cross sectional area of equipotential bonding conductors[32][33] connecting different bonding bars and of conductors connecting the bars to the earth termination system shall be 6 mm^2 (connection able to withstand induced lightning current) except the one for the earthing conductor of the class I tested SPD according to IEC 61643-11 that could be installed in point 4 (Figure 76): it shall be 16 mm^2.

Protection of the DC cable arriving to the modules is necessary: a bonding connection between the PV modules supporting structure and the bonding bar located near the inverter shall be done point 6 (Figure 76); this connection shall be positioned as close as possible to the DC cable to limit the length of the loop.

DC side

Usually 2 SPDs shall be installed on DC side; in accordance with IEC 61643-32 they shall be placed in point 1 and in point 2 (Figure 76).

SPD in point 2 (Figure 76) shall be Class II tested SPD according to IEC 61643-31.

SPD in point 1 (Figure 76) shall be Class II tested SPD according to IEC 61643-31; it is not required in case:

- the distance between the inverter and the PV field is l_1 < 10 m (ref. Figure 76) and SPD in point 2 (Figure 76) protection level (U_p) respect the following

— 32 Equipotential bonding conductors should comply with the requirements of IEC 60364-5-54, IEC 61643-12 and IEC 62305-3.

— 33 Local country requirements shall be taken into account.

— Equation 74

$$U_p \leq 0.8 \cdot U_w$$

Where:

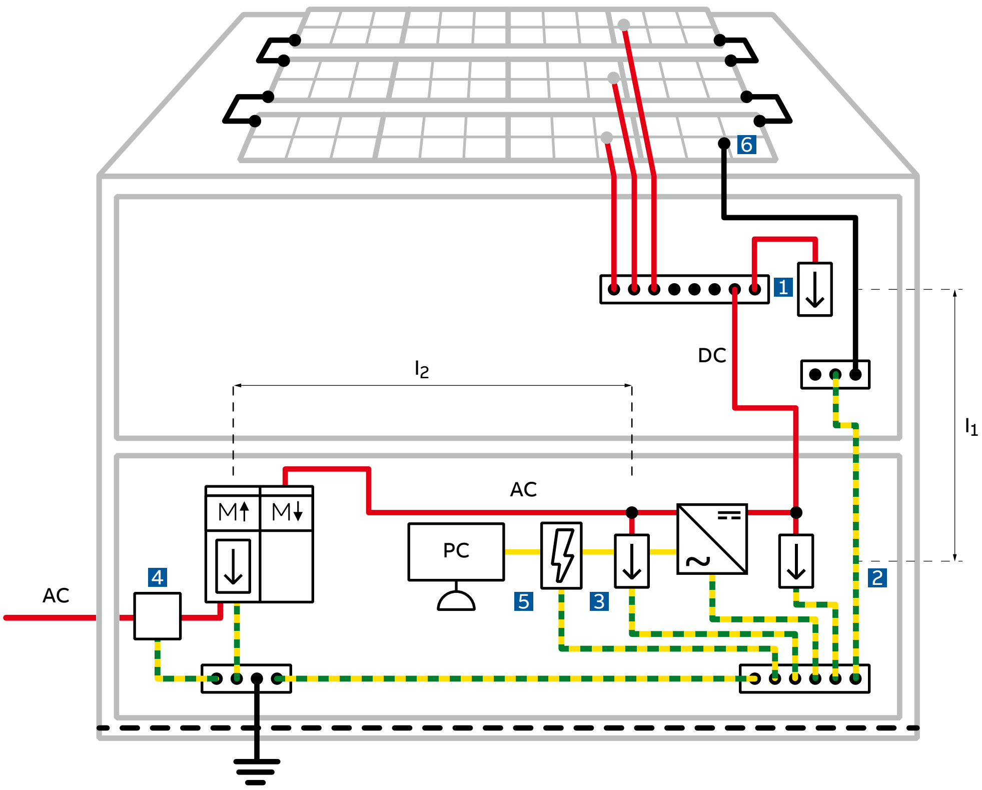
- U_w is the PV array's withstand voltage.
- PE conductor is routed close to the DC conductors and SPD in point 2 (Figure 76) protection level (U_p) respect the following

— Equation 75

$$U_p \leq 0.5 \cdot U_w$$

Where:

U_w is the PV array's withstand voltage.



— Figure 76 Building without external lightning protection system

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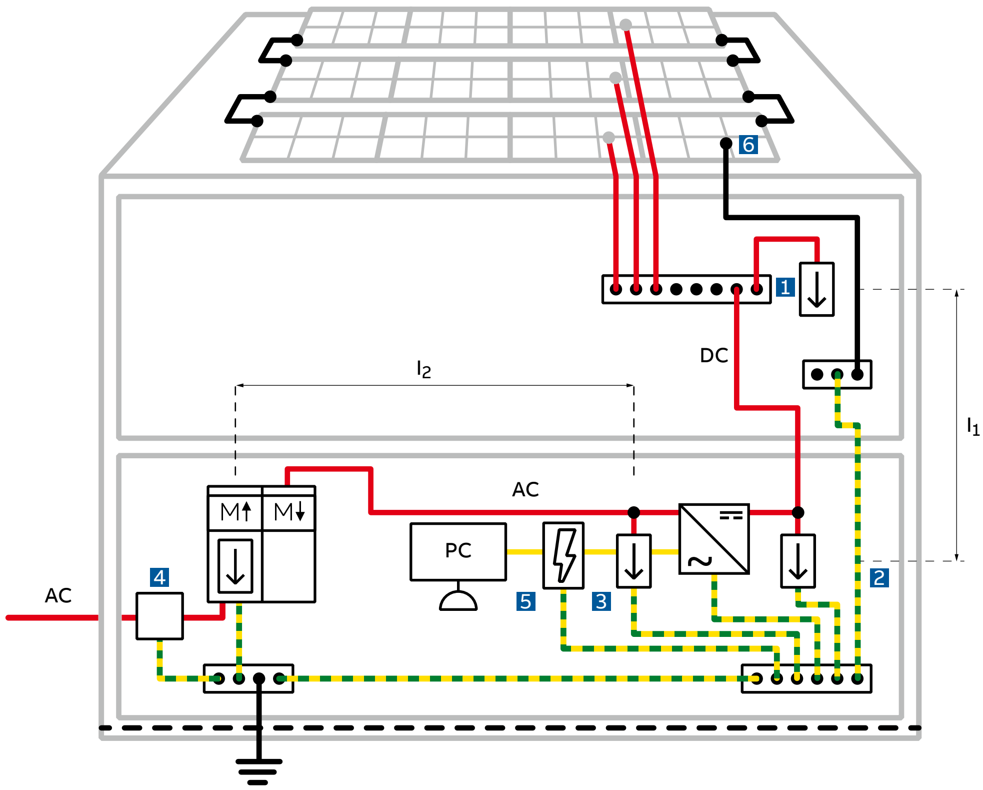


—
Figure 76
Building without external lightning protection system

AC side

Protection of the incoming AC electric line is necessary. Usually 2 SPDs shall be installed on AC side; in accordance with IEC 61643-32 they shall be placed in point 3 and in point 4 (Figure 76).
SPD in point 4 (Figure 76) shall be Class I or class II tested SPD according to IEC 61643-11.
SPD in point 3 (Figure 76) shall be Class II tested SPD according to IEC 61643-11; it is not required in case:

- the distance between the inverter and the main distribution board is l_2 < 10 m (ref. Figure 76) and the PE conductor is routed with the AC power conductors;
- inverter and main distribution board are connected to the same earthing bar with a cable length ≤ 0.5 m.

Data lines

If power conversion units are connected to data and sensor lines, SPD Category C for signal line according IEC 61643-21 shall also be installed in point 5 (Figure 76).

7.1.1.2 PV installations in Buildings with PV systems with external LPS and sufficient separation distance

The PV modules must be located in the protected zone of the isolated air-termination system and the separation distances must be maintained. Surge protective devices shall be installed in accordance with IEC 61643-32.

Equipotential bonding

Minimum cross sectional area of equipotential bonding conductors[34][35] connecting different bonding bars and of conductors connecting the bars to the earth termination system shall be 6 mm² (connection able to withstand induced lightning current) except the one for the earthing conductor of the class I tested SPD according to IEC 61643-11 that shall be installed in point 4 (Figure 77): it shall be 16 mm². Protection of the DC cable arriving to the modules is necessary: a bonding connection between the PV modules supporting structure and the bonding bar located near the inverter shall be done point 6 (Figure 77); this connection shall be positioned as close as possible to the DC cable to limit the length of the loop.

— 34 Equipotential bonding conductors should comply with the requirements of IEC 60364-5-54, IEC 61643-12 and IEC 62305-3.

— 35 Local country requirements shall be taken into account.

DC side

Usually 2 SPDs shall be installed on DC side; in accordance with IEC 61643-32 they shall be placed in point 1 and in point 2 (Figure 77). SPD in point 2 (Figure 77) shall be Class II tested SPD according to IEC 61643-31. SPD in point 1 (Figure 77) shall be Class II tested SPD according to IEC 61643-31; it is not required in case:

- the distance between the inverter and the PV field is l_1 < 10 m (ref. Figure 77) and SPD in point 2 (Figure 77) protection level (U_p) respect the following

— Equation 76

$$U_p \leq 0.8 \cdot U_w$$

Where:

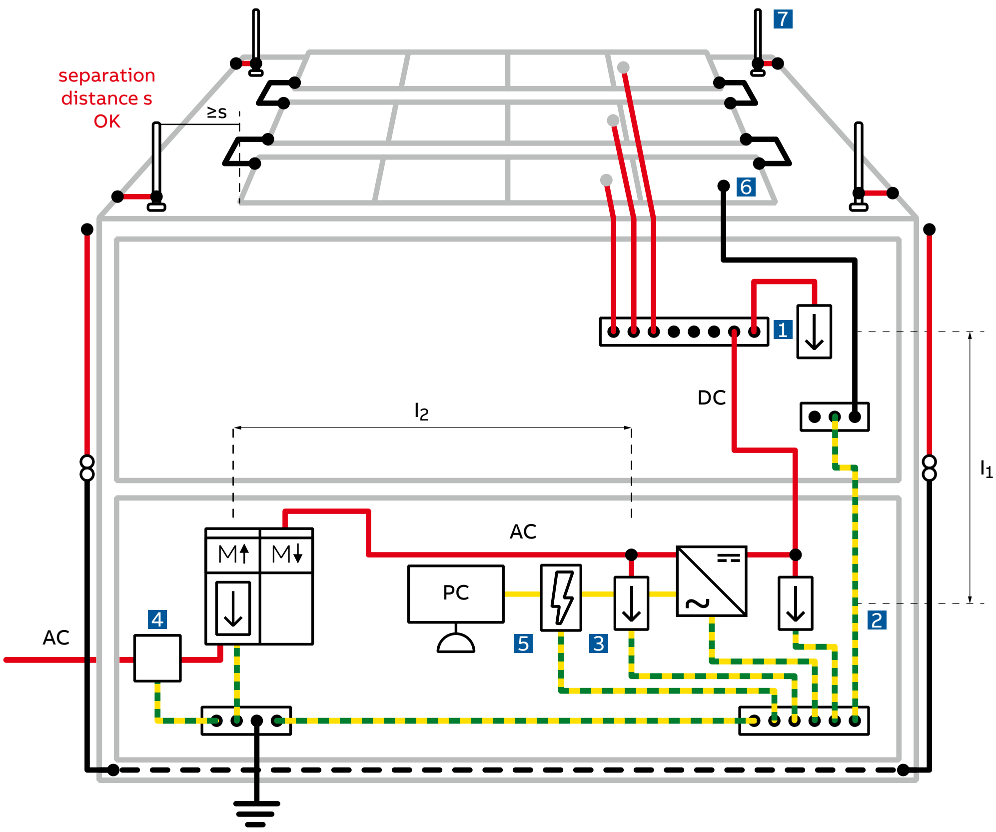
- U_w is the PV array's withstand voltage.
- PE conductor is routed close to the DC conductors and SPD in point 2 (Figure 77) protection level (U_p) respect the following

— Equation 77

$$U_p \leq 0.5 \cdot U_w$$

Where:

U_w is the PV array's withstand voltage.



— Figure 77 Building with external lightning protection system and sufficient separation distance

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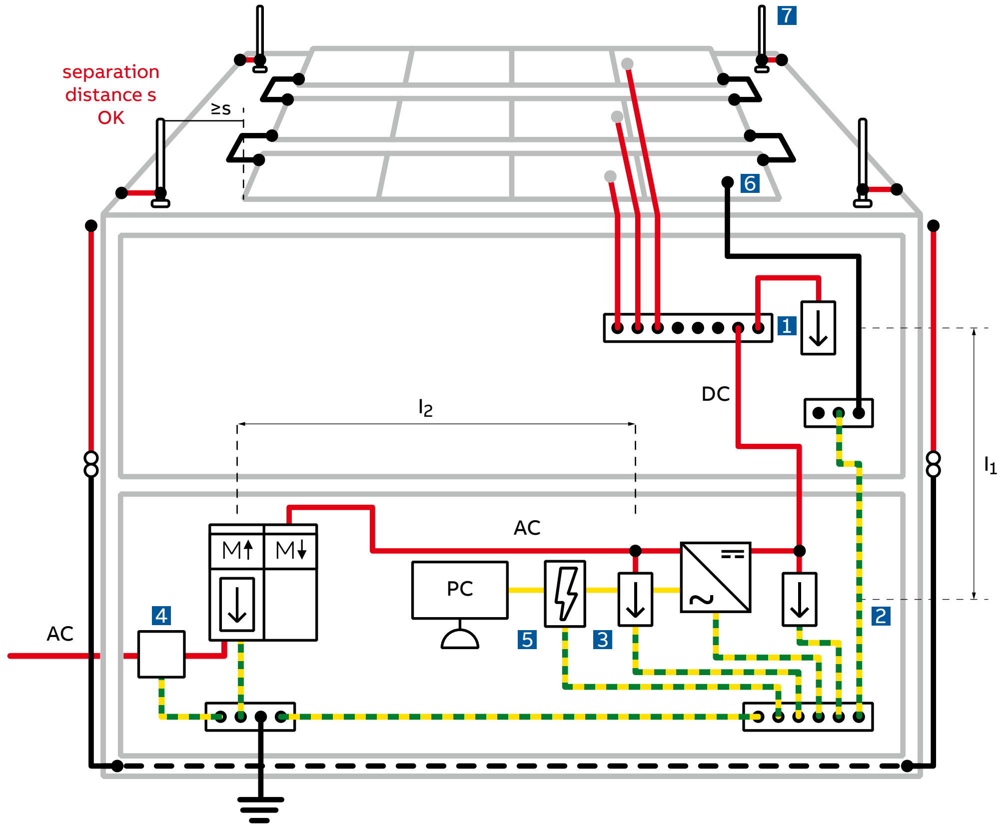
Figure 77
Building with external lightning protection system and sufficient separation distance



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36
Reference to IEC 62305-4.

AC side

Protection of the incoming AC electric line is necessary. Usually 2 SPDs shall be installed on AC side; in accordance with IEC 61643-32 they shall be placed in point 3 and in point 4 (Figure 77).
SPD in point 4 (Figure 77) shall be Class I tested SPD according to IEC 61643-11.
SPD in point 3 (Figure 77) shall be Class II tested SPD according to IEC 61643-11; it is not required in case:

- the distance between the inverter and the main distribution board is $l_2 < 10$ m (ref. Figure 77) and the induced voltage to lightning current flowing in the down conductor can be ignored[36];
- inverter and main distribution board are connected to the same earthing bar with a cable length ≤ 0.5 m.

Data lines

If power conversion units are connected to data and sensor lines, SPD Category C for signal line according IEC 61643-21 shall also be installed in point 5 (Figure 77).

7

7.1.1.3 PV installations in Buildings with PV systems with external LPS, without enough separation distance

If the separation distances cannot be maintained, for example in case of a metal roof, lightning equipotential bonding must be implemented and surge protective devices shall be installed in accordance with IEC 61643-32.

Equipotential bonding

Minimum cross sectional area of equipotential bonding conductors[37 38] connecting different bonding bars and of conductors connecting the bars to the earth termination system shall be 16 mm² (connection able to withstand partial lightning current). Protection of the DC cable arriving to the modules is necessary: a bonding connection between the PV modules supporting structure and the bonding bar located near the inverter shall be done in point 6 (Figure 78); this connection shall be positioned as close as possible to the DC cable to limit the length of the loop.

—
37
Equipotential bonding conductors should comply with the requirements of IEC 60364-5-54, IEC 61643-12 and IEC 62305-3.

—
38
Local country requirements shall be taken into account.

DC side

Usually 2 SPDs shall be installed on DC side; in accordance with IEC 61643-32 they shall be placed in point 1 and in point 2 (Figure 78).
SPD in point 2 (Figure 78) shall be Class I tested SPD according to IEC 61643-31 and it shall be installed as close as possible to the inverter.
SPD in point 1 (Figure 78) shall be Class I tested SPD according to IEC 61643-31 and it shall be installed as close as possible to the PV field.

AC side

Protection of the incoming AC electric line is necessary. Usually 2 SPDs shall be installed on AC side; in accordance with IEC 61643-32 they shall be placed in point 3 and in point 4 (Figure 78).
SPD in point 4 (Figure 78) shall be Class I tested SPD according to IEC 61643-11.
SPD in point 3 (Figure 78) shall be Class I tested SPD according to IEC 61643-11 and it shall be installed as close as possible to the inverter. It is not required in case inverter and main distribution board are connected to the same earthing bar with a cable length ≤ 0.5 m.

Data lines

If power conversion units are connected to data and sensor lines, SPD Category C for signal line according IEC 61643-21 shall also be installed in point 5 (Figure 78).

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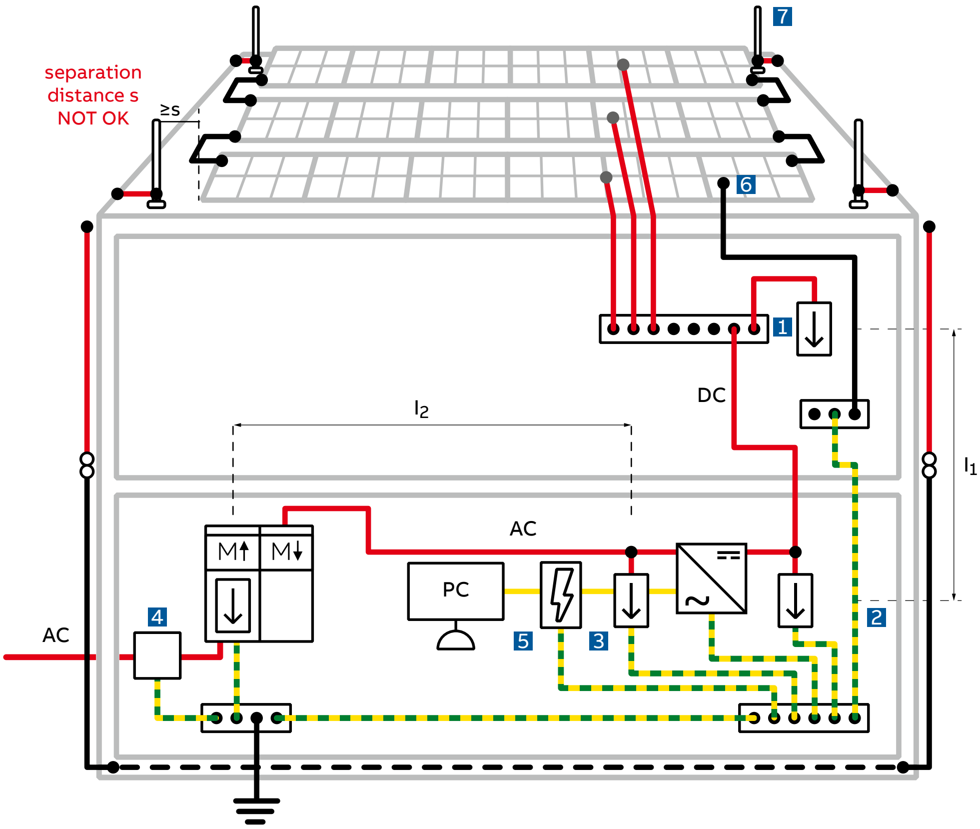
Figure 78
Building with external lightning protection system but insufficient separation distance



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7.1.2 Free field PV systems

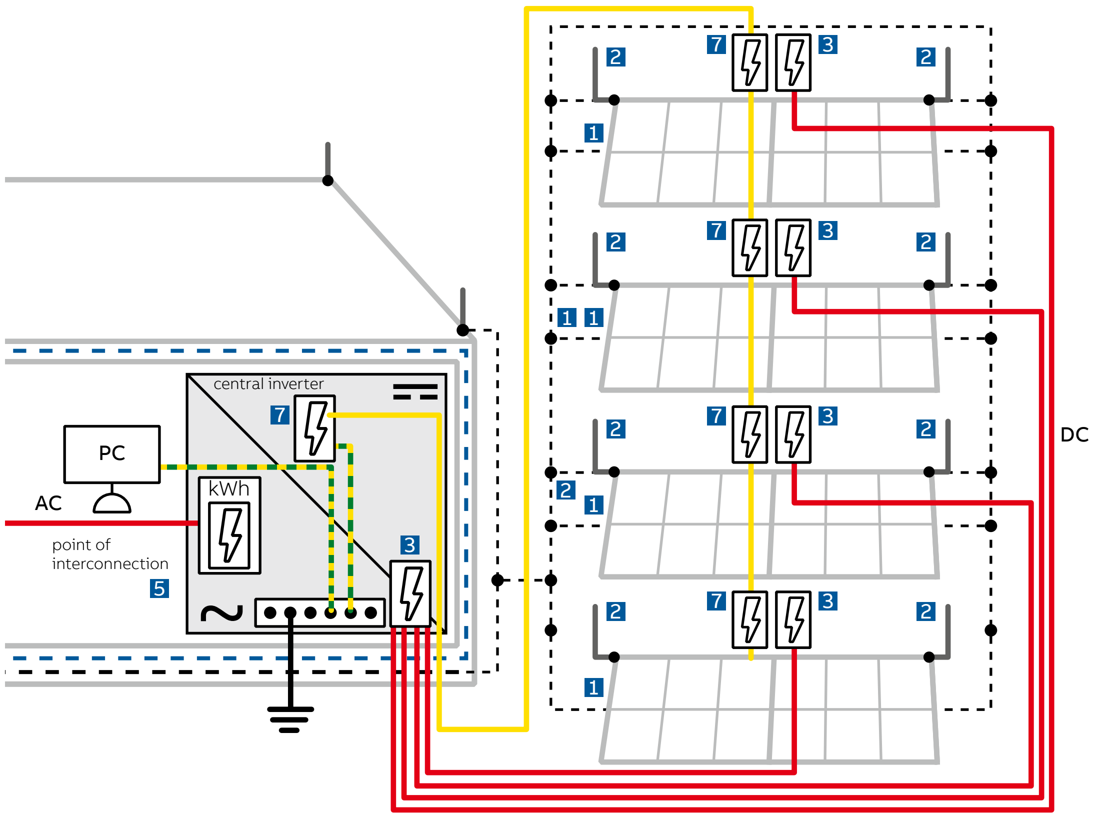
IEC 61643-32 describe protective measures for free field PV systems. Meshed earthing system is the basis for an effective lightning and surge protection system: it produces a large equipotential surface and then, in case of lightning interference, significantly reduces the voltage interference of electrical connecting cables. In the selection of SPDs, 2 different configurations shall be considered:

- free field PV systems with central inverter;
- free field PV systems with string inverters.

7.1.2.1 Free field PV systems with central inverter

First of all, the collection area should be analysed to determine whether the structure is exposed.
When the structure is not exposed, protection of the DC cable arriving to the modules is necessary: a bonding connection between the PV modules supporting structure and earth-termination system should be done in point 1 (Figure 79).
If the structure is exposed, a lightning protection system (LPS) must be provided. Protection of the DC cable arriving to the modules is also necessary: a bonding connection between the PV modules supporting structure and LPS should be done in point 1 and point 2 (Figure 79) through a conductor with a cross-section of at least 16 mm².
If lightning strikes in the PV system area, partial lightning currents are coupled into the equipotential bonding system. Therefore, free field PV systems with central inverter shall be protected on the DC side using type 1 SPDs in point 3 (Figure 79).
Free field PV systems with central inverter are generally quite large and are located in rural and remote areas. They are typically supplied by a MV three-phase line, which is unshielded and may be many km long. Such line arrives at a MV/LV transformer, on the load side of which there is the inverter.
SPD could be installed in the MV line.
Protection of the incoming AC electric line to the inverter is necessary: protection can be obtained with a Class I SPDs in point 5 (Figure 79).

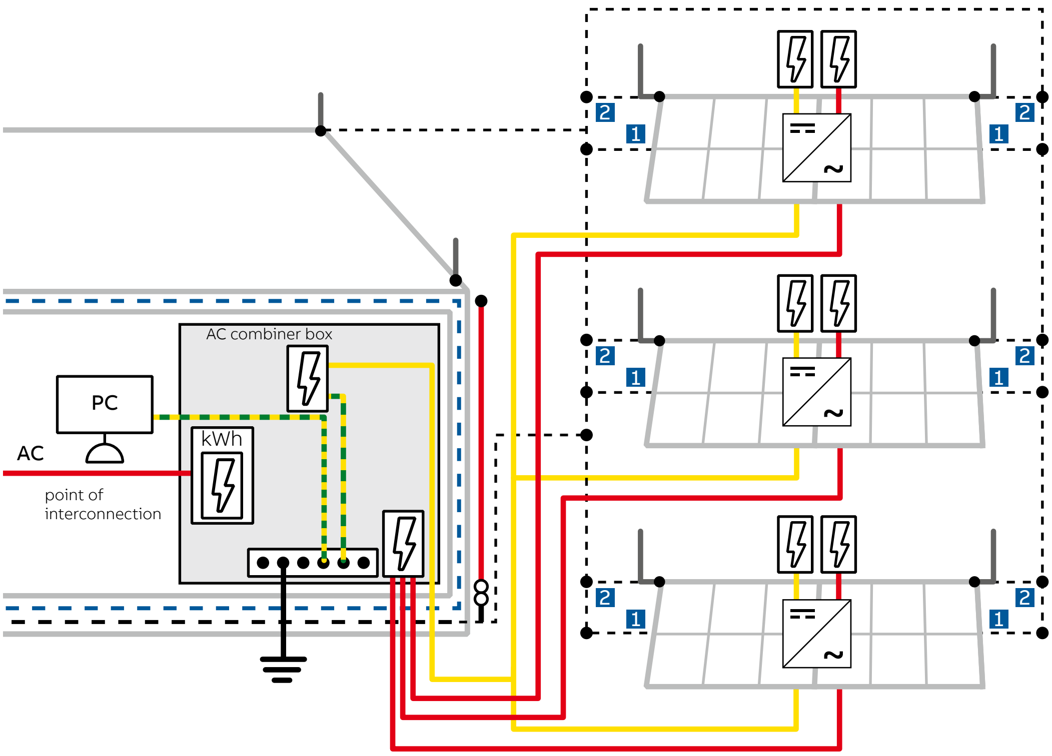
—
Figure 79
Free field PV systems with central inverter



7.1.2.2 Free field PV systems with string inverters

First of all, the collection area should be analysed to determine whether the structure is exposed.
When the structure is not exposed, protection of the DC cable arriving to the modules is necessary: a bonding connection between the PV modules supporting structure and earth-termination system should be done in point 1 (Figure 80).
If the structure is exposed, a lightning protection system (LPS) must be provided. Protection of the DC cable arriving to the modules is also necessary: a bonding connection between the PV modules supporting structure and LPS should be done in point 1 and point 2 (Figure 80) through a conductor with a cross-section of at least 16 mm².
In the free field PV systems with string inverters, the string inverters are installed near the PV panels to protect the DC side, it is sufficient to use type 2 SPDs with a discharge capacity of at least 5 kA (8/20 µs) per mode of protection.
Protection of the incoming AC electric line to the inverter is necessary: protection can be obtained with a Class I SPDs.
Free field PV systems, with string inverters, are generally quite large and are located in rural and remote areas. They are typically supplied by a MV three-phase line, which is unshielded and may be many km long. Such line arrives at a MV/LV transformer, on the load side of which there is the inverter. SPD could be installed in the MV line.

—
Figure 80
Free field PV systems with string inverters



7.1.2.3 Data lines

Attention shall be paid since a telecom line often enters the PV plant, for the control and monitoring of the plant itself. If power conversion units are connected to data and sensor lines, SPD Category C for signal line according IEC 61643-21 shall also be installed in point 7 (Figure 79).

7.1.3 Selection of SPDs

7.1.3.1 Selection of SPDs on the AC side

General requirements for AC side SPDs are provided by IEC 60364-5-53:2015, Clause 534, IEC 61643-12 and IEC 62305-4.

Nominal discharge current I_n and impulse current I_{imp}
For the test class II AC SPDs, the minimum nominal discharge current I_n for each mode of protection shall be 5 kA (8/20 µs). The use of class II SPDs with a higher I_n allows to obtain longer lifetime.
For the test class I AC SPDs, the SPDs shall provide a minimum impulse current I_{imp} as required by IEC 60364-5-53:2015, Clause 534 and IEC 61634-12.
I_{imp} depends on the risk according to the Lightning Protection Level (LPL). A simplified approach to define I_{imp} is provided by IEC 61643-12.

Voltage protection level U_p
To correctly define the AC SPD with the appropriate voltage protection level (U_p), the rated impulse voltage U_w of the equipment shall be known.
U_p must be around 20% lower than the U_w.

—
Equation 78

$$U_p \leq 0.8 \cdot U_w$$

7.1.3.2 Selection of SPDs on the DC side

General requirements for DC side SPDs are provided by IEC 60364-7-712. Detailed requirements for DC side SPDs are provided by IEC 61643-32.

Nominal discharge current I_n and impulse current I_{imp}
For the test class II DC SPDs, the minimum nominal discharge current I_n for each mode of protection shall be 5 kA (8/20 µs). The use of class II SPDs with a higher In allows to obtain longer lifetime.
For the test class I DC SPDs, the SPDs shall provide a minimum impulse current I_{imp}.
I_{imp} depends on the Lightning Protection Level (LPL) and on SPD technology used (SPD technology influences itself the distribution of lightning current in the system; SPD has to discharge surge currents of different magnitudes based on the technology): according to LPL and SPD technology used (voltage-limiting SPDs or voltage-switching SPDs), IEC 61643-32 defines the required discharge capacity for the SPDs to be used.

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Table 4
IEC 61643-32 values for voltage-limiting SPDs MOVs (Metal Oxide Varistors) or MOVs connected in series to GDTs (Gas Discharge Tubes) in the PV application on a building where the separation distance is not maintained.

Lightning protection class LPL	Max lightning surge current (10/350 µs)	Number of external protective devices							
		<4				≥4			
		Per mode of protection		I_{total}		Per mode of protection		I_{total}	
		$I_{8/20}$	$I_{10/350}$	$I_{8/20}$	$I_{10/350}$	$I_{8/20}$	$I_{10/350}$	$I_{8/20}$	$I_{10/350}$
I or unknown	200 kA	17 kA	10 kA	34 kA	20 kA	10 kA	5 kA	20 kA	10 kA
II	150 kA	12,5 kA	7,5 kA	25 kA	15 kA	7,5 kA	3,75 kA	15 kA	7,5 kA
III or IV	100 kA	8,5 kA	5 kA	17 kA	10 kA	5 kA	2,5 kA	10 kA	5 kA

—
Table 5
IEC 61643-32 values for voltage-switching SPDs GDTs (Gas Discharge Tubes) or GDTs connected in parallel to MOVs (Metal Oxide Varistors) in the PV application on a building where the separation distance is not maintained.

Lightning protection class LPL	Max lightning surge current (10/350 µs)	Number of external protective devices			
		<4		≥4	
		Per mode of protection		Per mode of protection	
		$I_{10/350}$	I_{total}	$I_{10/350}$	I_{total}
I or unknown	200 kA	25 kA	50 kA	12,5 kA	25 kA
II	150 kA	18,5 kA	37,5 kA	9 kA	18 kA
III or IV	100 kA	12,5 kA	25 kA	6,25 kA	12,5 kA

—
Table 6
IEC 61643-32 values for voltage-limiting SPDs and voltage-switching SPDs in DC side of in free-standing PV systems with a central power inverter.

Lightning protection class LPL	max lightning surge current (10/350 µs)	SPDs on the DC side I_{imp} in kA (10/350 µs), I_n in kA (8/20 µs)					
		Voltage-limiting SPDs				Voltage-switching SPDs	
		MOV		MOV + GDT in series		GDT	MOV + GDT parallel
		$I_{10/350}$		$I_{8/20}$		$I_{10/350}$	
		Per mode of protection	I_{total}	Per mode of protection	I_{total}	Per mode of protection	I_{total}
III or IV	100 kA	5 kA	10 kA	15 kA	30 kA	10 kA	20 kA

Maximum continuous operating voltage U_{CPV}
The SPD's maximum continuous operating voltage (U_{CPV}) shall be higher than the maximum open circuit voltage of the PV array (at least equal to the maximum open circuit voltage of the PV array).

Short circuit current rating I_{SCPV}
In order to avoid possible hazard to people and property caused by DC arcing, the SPD's short-circuit current rating (I_{SCPV}) shall be equal to or greater than the maximum short-circuit current available from the PV array at the installation point of the SPD.
The SPD shall be equipped with a dedicated protective device (usually fuse) able to operate under the current level provided by the PV array[39].

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39
Unless the SPD has internal means for short-circuit the SPD, able to handle IscPV for an unlimited time to reach a safe failure mode.

Voltage protection level UP
To correctly define the DC SPD with the appropriate voltage protection level (U_p), the rated impulse voltage U_w of the equipment shall be known.
U_p must be around 20% lower than the U_w.

—
Equation 79

$$U_p \leq 0.8 \cdot U_w$$

7

Annex A – New technologies

Annex A – New technologies

A.1 Cells: development and emerging technologies

In the paragraph 1.3 the actual technology about crystal silicon modules and about thin-film modules were already described. The cost reduction in PV production processes is the driver for technology development in the PV field. Here below the major technology developments that are interesting for wafer-based crystalline silicon (c-Si) cells and modules:

- Reduction of polysilicon utilization per wafer: this goal could be reached producing thinner wafers, reducing kerf loss and increasing recycling rates;
- Reduction of consumable material used in the crystalline cells production: this goal could be reached reducing the metallization pastes/inks containing silver (Ag) and aluminum (Al);
- Reduction of row material consumption in the PV module production: the industry is reducing the consumption of cells interconnection material and it is reducing also the thickness of the front glass used as PV modules frontsheet.
- Improvement of cells energy conversion: in order to increase the modules performances, the industry is working on cells texturing technologies, cells rear side passivation technologies, improvement of phosphorous emitter technologies for p-type cells, improvement of technologies for boron doping for n-type cells, cells front side metallization technologies, reduction of resistive loss related to cells interconnection (increasing of busbars number), improvements on the bifacial cells technology, improvement on the solar spectrum utilization (multi junction solar cells);
- Improvement on the PV modules layout and dimensions:
  the cells dimensions grew from 156 mm x 156 mm to 156.75 mm x 156.75 mm;
  the roadmaps assume that the larger format of 161.75 mm x 161.75 mm will gain significant market share in the next years.

The major technology developments that are interesting for the **thin film technologies (CIS, CIGS, CdTe, CZTS, a-Si)** are:

- Technology improvement: in order to replace/amend usage of some scarce and strategic materials (e.g., Te, In, Ga, etc) improvements of material used in a thin film are ongoing;
- Module efficiency improvement: to be cost-competitive compared to other technology the thin film industry is going to reduce the non-active interconnection zones and also reduce the degradation mechanism;
- Improvement of energy conversion: new type of anti-reflective, anti-soiling and anti-abrasive coatings are in developing phase.

The CIGS is a mature technology; it is growing for BIPV application; laboratories achieved 21 % efficiency.
The a-Si is a mature technology, but it is declining; it could be used for flexible and semi-transparent PV applications; laboratories achieved 10 % efficiency.
The CdTe is a mature technology and it is growing; it could be used for utility scale application in hot areas; laboratories achieved 21 % efficiency.

New different technologies are being the subject of research and development activities.
Dye sensitized solar cells DSSC are also known as Grätzel cells from the name of their inventor: DSSC is based on organic material and it consist of a glass or plastic frontsheet with few elements deposited one upon the other:

- a thin film conductive transparent electrode;
- a porous nanocrystal layer of the semiconductive titanium dioxide ($Ti0_2$);
- dye molecules (metal-organic complexes of ruthenium) distributed on the $Ti0_2$ surface;
- an electrolyte formed by an organic solvent and a redox pair as iodide/trioxide;
- a platinum-catalyzed counter electrode.

The dye is the photoactive material of DSSC; it can produce electricity once it is sensitized by light. The dye catches photons of incoming light (sunlight and ambient artificial light) and it uses their energy to excite electrons (its behaviour is like chlorophyll in photosynthesis). The excited electrons are injected into the titanium dioxide (TiO_2). The electrons are conducted away by nanocrystalline titanium dioxide. The chemical electrolyte closes the circuit so that the electrons are returned back to the dye. The electrons' movement create energy.

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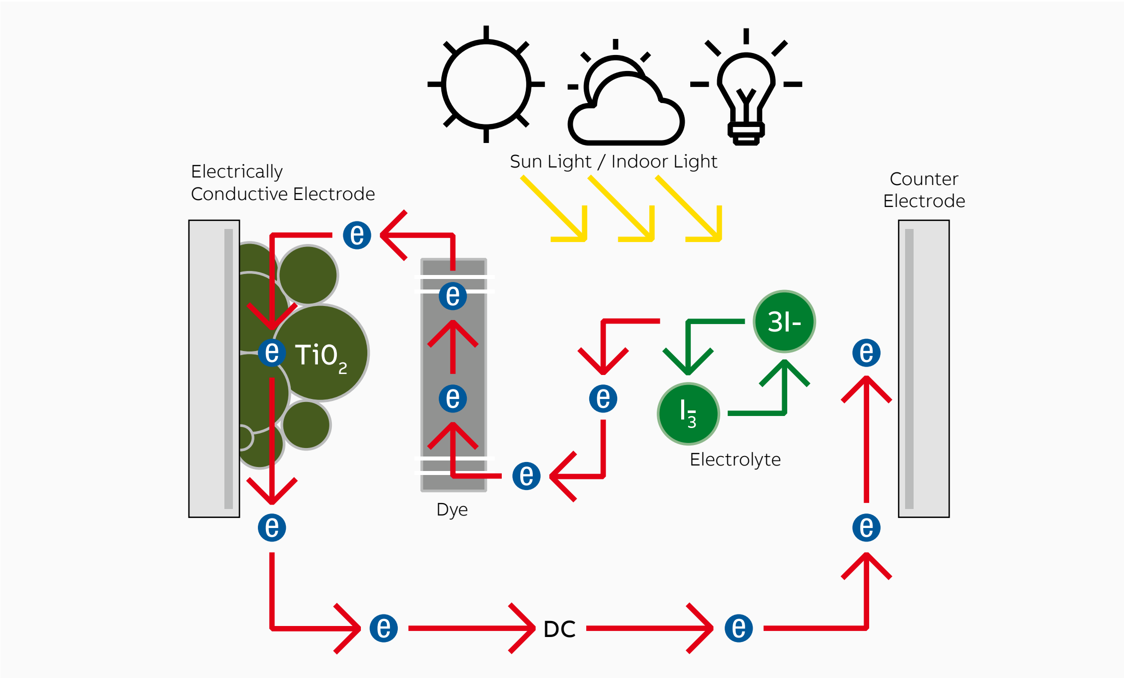
Figure 81
DSSC cells scheme



The theoretical photoelectric conversion efficiency limit of the DSSC, using a simple junction configuration, under standard test conditions (STC) is 32%. A two levels tandem DSSC could reach 46 % efficiency. In laboratories 12 % efficiency has been already achieved by DSSC cell.
The DSSC is a niche technology: it is colour attractiveness.

Organic solar cells (OSC) or organic photovoltaics (OPV): vacuum deposition is used to produce organic solar cells using low-molecular-weight materials. Organic materials having p-type and n-type conductivities are deposited on a transparent electrode, and then, a metal electrode is deposited on them.

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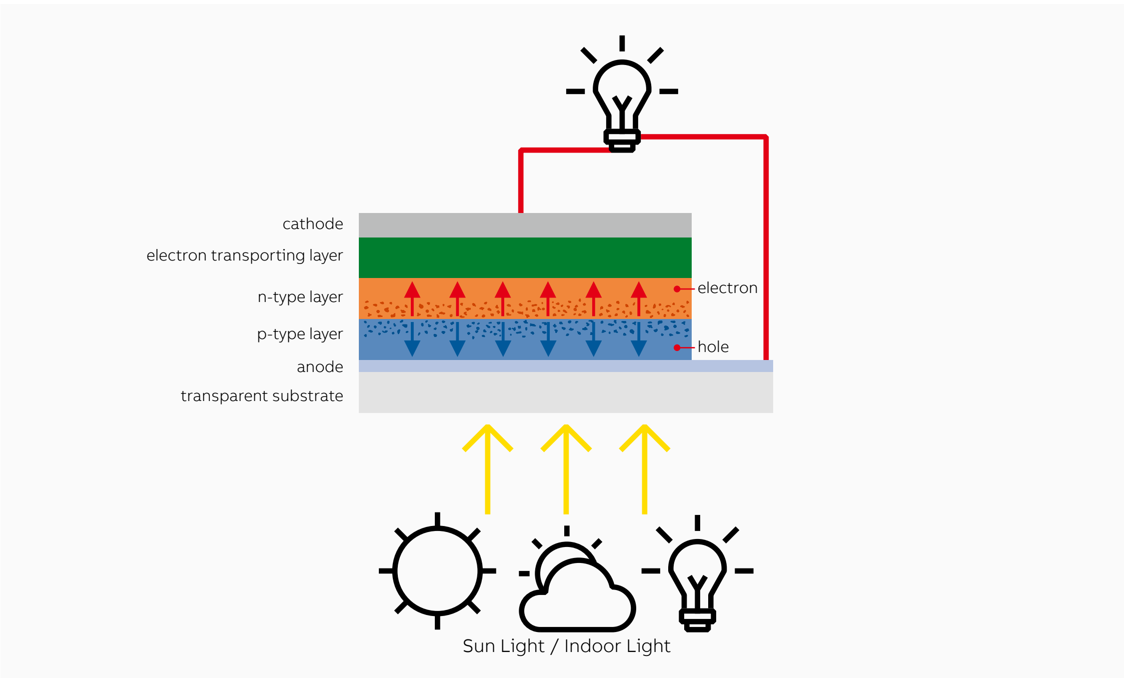
Figure 82
OSC cells scheme



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Sunlight is absorbed by organic layers in OSC, and excitations generated by light absorption are dissociated to electrons and holes at the interface between p-type and n-type organic layers.
The electrons and holes are collected at the upper and lower electrodes, respectively, and electricity is generated. Example of organic materials that can be used for PV applications: P3HT, Phtalocyanine, PCBM and Ruthenium Dye N3. In the hybrid cells the active material can be a mixture of organic molecules and of nanoparticles of inorganic compounds (e.g. carbon nanotubes). Organic semiconductors have the capabilities necessary to reach in the medium-long term the aim of producing PV panels at low cost, since they can be synthesized and then deposited, at low temperature and with a low industrial cost, on a large area also on flexible sub-layers. For the time being, the main limit of this typology is its conversion efficiency (<10 % for a mini module).
The OSC is a pilot niche technology: it is colour attractiveness.

The Perovskite Solar Cells (PSC) Perovskite based thin film PV is not yet in production, but this technology has made remarkable progress in the past few years. Because of its potential of very low-cost production, and it is suitable bandgap for tandem formation with crystalline silicon, it could revolutionize PV energy generation. Perovskite Solar Cells could be with and without lead content. Laboratories achieved 16 % efficiency for Perovskite Solar mini module.

The quantum dot solar cell (QDSC) is a kind of solar cell that uses quantum dots as the absorbing PV material. It has the potential to increase the maximum attainable thermodynamic conversion efficiency of photovoltaic conversion up to about 66%. It attempts to replace bulk materials such as silicon, copper indium gallium selenide (CIGS) or cadmium telluride (CdTe).

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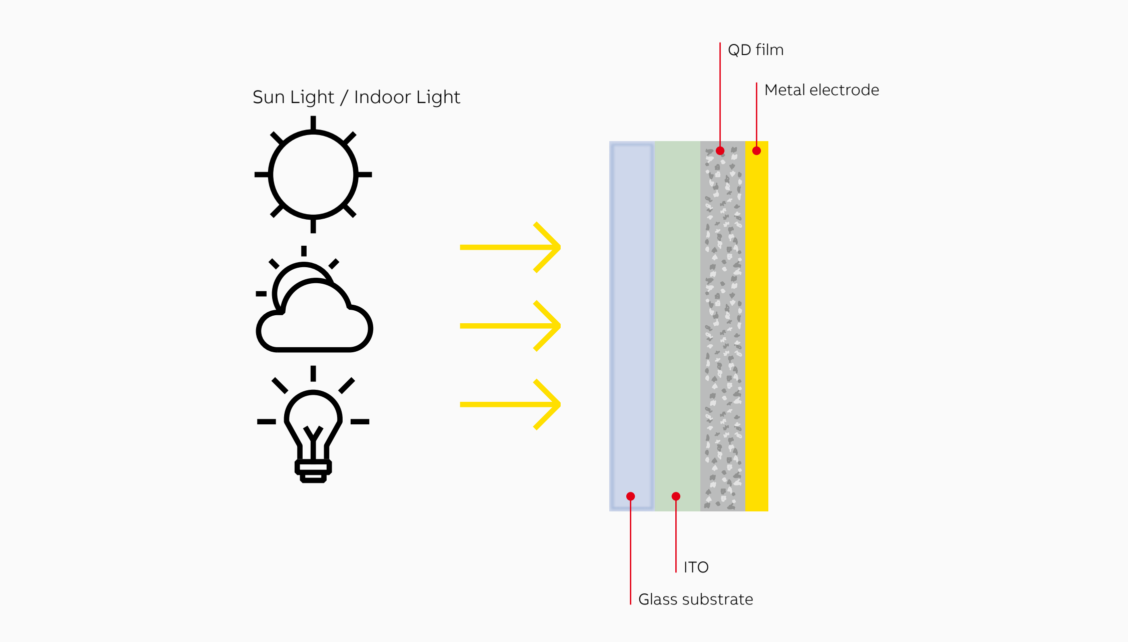
Figure 83
QDSC cells scheme



The quantum dots film is attractive for multi-junction solar cells, where a variety of materials are used to improve efficiency by harvesting multiple portions of the solar spectrum.
Laboratories achieved 14 % conversion for QDSC.

The **III-V (speak threefive)** PV technology is a thinfilm technologies (semiconductor materials are deposited on a substrate) with the highest conversion efficiencies under both one sun standard test conditions and concentrated sun conditions. The III-V PV technology is very expensive. Such cells are usually used for space-applications and in concentrator technology, where high performance is more important that the cost. The III-V materials are based on the elements with three valence electrons like aluminium (Al), gallium (Ga) or indium (In) and elements with five valence electrons like phosporus (P) or arsenic (As). Various different semiconductor materials have been explored: gallium arsenide (GaAs), gallium phosphide (GaP), indium phosphide (InP), indium arsenide (InAs), GaInAs, GaInP, AlGaInAs and AlGaInP. III-V PV devices can reach very high efficiencies when they are based on the multi-junction concept, which means that more than one band gap is used.

A.2 Concentrator photovoltaics (CPV)

Concentrator photovoltaics (CPV) is a photovoltaic technology that focus sunlight onto small, highly efficient, solar cells. The classification of concentrator systems could be done according to different criteria:
- The concentration level:
- The cooling system: passive or active;
- The optical component: lenses or mirror;
- The shape of the optics: point focus, linear, etc;
- The cell material or the cell structure: silicon, III–V semiconductors, single-junction, multijunction;
- The tracking strategy: two-axis, single-axis, stationary, quasi-stationary, etc.

The key principle of CPV is reduce the PV installation occupation of the land and reduce the levelized cost of electricity (LCOE). Concentrating photovoltaics implies more complex plant design and engineering due to:
- The necessity of installing the plants in areas with high direct solar radiation, which makes the analysis of the characteristics of the location quite difficult in the design phase and reduces the number of the areas suitable for such plants;
- The necessity of an accurate tracking system to keep the module as perpendicular as possible to direct solar radiation;
- The necessity of a cooling system for the cells because of the high temperature they can reach due to the increased irradiance; the operating temperature must be kept lower than 200-250°C through air-cooling systems (plate fin heat exchangers) or liquid cooling systems (with micro-tubes and possibility of using the heat taken for co-generation).

CPV systems are categorized according to the solar concentration, measured in "suns":
- Low concentration PV (LCPV): the solar concentration of LCPV is from 2 suns to 100 suns. Usually the LCPV uses conventional or modified silicon solar cells. The cooling of the cells is obtained with passive cooling system.
- Medium concentration PV: the solar concentration of Medium concentration PV is from 100 suns to 300 suns. The cooling of the cells could be passive or active; this kind of CPV needs to be installed on 2 axis solar tracker to optimize the focus of CPV on the solar cells.
- High concentration PV (HCPV): the solar concentration of HCPV is from 300 suns to 1000 suns (or more). The cooling of the cells is usually active; this kind of CPV needs to be installed on 2 axis solar tracker to optimize the focus of CPV on the solar cells. Often Multi-junction solar cells are used because they are more efficient and have lower temperature coefficients.

The CPV are complex systems used only for utility scale installations; a lot of standards were developed to assure the safety, reliability and performance of CPV Systems:
- IEC 62108 - Concentrator photovoltaic (CPV) modules and assemblies - Design qualification and type approval;
- IEC 62670 series - Photovoltaic concentrators (CPV) - Performance testing;
- IEC 62688 - Concentrator photovoltaic (CPV) modules and assemblies - Safety qualification;
- IEC 62925 - Concentrator photovoltaic (CPV) modules - Thermal cycling test to differentiate increased thermal fatigue durability;
- IEC 62817 - Photovoltaic systems - Design qualification of solar trackers;
- UL 3703 - Standard for Solar Trackers;
- UL 8703 - Outline of Investigation for Concentrator Photovoltaic Modules and Assemblies.

The CPV strengths are:
- High efficiencies under direct normal irradiance;
- Low temperature coefficients;
- Increased and stable energy production throughout the day due to (two-axis) tracking;
- Low energy payback time;
- Potential double use of land e.g. for agriculture, low environmental impact;
- Greater potential for efficiency increases in the future compared to single-junction flat plate systems could lead to greater improvements in land area use, BOS costs, and BOP costs.

The CPV weaknesses are:
- HCPV cannot utilize diffuse radiation. LCPV can only utilize a fraction of diffuse radiation;
- Tracking with sufficient accuracy and reliability is required;
- Optical losses;
- May require frequent cleaning to mitigate soiling losses, depending on the site.

A.3 Floating PV systems

In the floating solar or FPV (Floating photovoltaic) the arrays of solar panels are located on a structure that floats on a body of water, typically an artificial basin or a lake.

The reasons for the development of these system are:
- No land occupancy;
- Water saving and water quality: the partial coverage of basins can reduce the water evaporation.
- Installation and decommissioning: no fixed structures are used for the installation; no foundations are required; the installation can be totally reversible.
- Cooling: a subtle water layer circulating over the panel surface keeps the module temperature at values such as to guarantee the maximum efficiency. This increases the annual energy production by about 10 %, which exceeds the consumption of the pump guaranteeing cooling;
- Solar tracking: since the floating platform can operate as a solar tracker with one degree of freedom, that is moving in the East-West direction over the day, thus ensuring an increase in the annual producibility up to 25 %.

Nonetheless, there are some disadvantages which still make the use of floating systems difficult:
- Still unknown the effects, over long periods, of the constant flow of the water on the modules and of their interaction with the aquatic vegetation and wildlife;
- Extra-costs (about 0.8 €/W) due to the floating structure and to the tracking and cooling systems: about 50 % increase in the total cost if compared with one installation of the same size on a roof or on the ground.

8

Annex B – Design examples of photovoltaic plants

Annex B – Design examples of photovoltaic plants

Introduction

Here are two design examples of a photovoltaic power plant utility scale grid-connected.
The first example refers to a photovoltaic power plant utility scale grid-connected designed using central inverters. The second example refers to a photovoltaic power plant utility scale grid-connected designed using string inverters. In both cases the PV plants are connected to the MV public utility network. An IT earthing system is used in both cases on DC side.
In accordance with IEC 62548, a means shall be provided to measure the insulation resistance from the PV array to earth: it could be included in the inverter; in any case the presence of insulation measuring device shall be verified. Finally, in both cases, the prospective short-circuit current delivered by the distribution network is assumed to be 12.5 kA three-phase.

B.1 PV plant with central inverters (3-4MW)

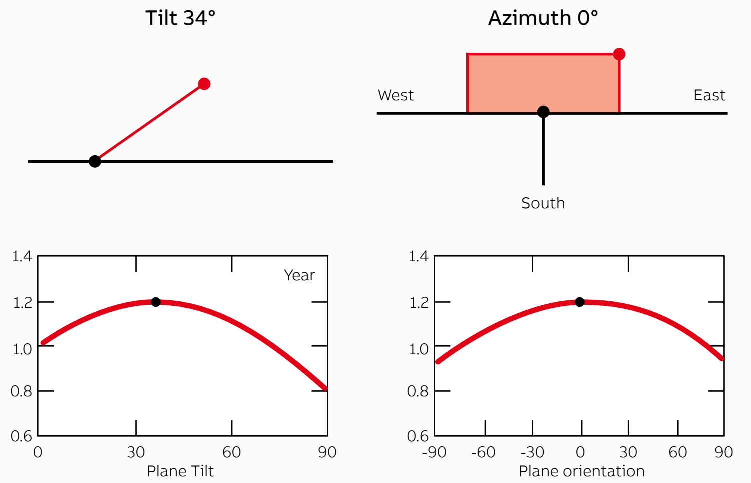
We wish to carry out the design of a PV plant utility scale grid-connected; it shall be connected to the MV public utility network (20 kV / 50 Hz).
The PV plant will be ground-mounted with fix free standing PV array; it will be situated in a land in the center of Italy near to the city of Rome. The land is completely flat and it covers 6.6 hectares.

B.1.1 Inclination and orientation of the modules

The fixed modules will be oriented to south and then the Azimuth angle (γ) will be 0.
The optimal tilt angle (slope of the PV modules) in Rome (41°53'N 12°12'E) that gives the highest energy output for the whole year, assuming that the slope angle stays fixed for the entire year, is 34° (the optimal slope angle could be calculated by free online solar photovoltaic calculator tool: e.g. PVGIS http://re.jrc.ec.europa.eu/pvg_tools/en/tools.html#PVP)

6

—
Figure 84
optimal tilt angle
and orientation



B.1.2 Site reference temperature

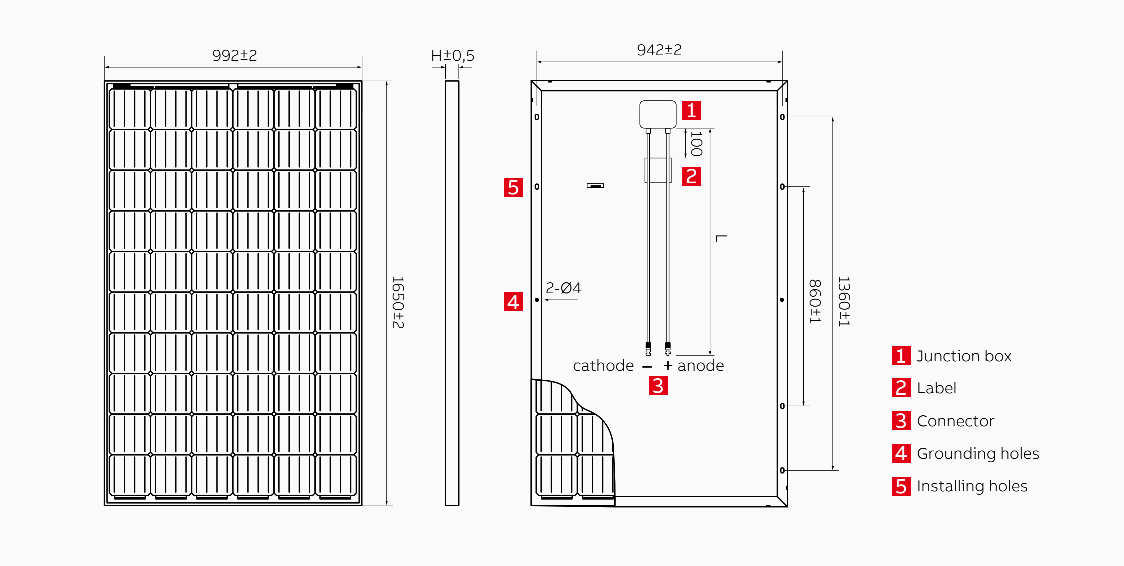
The maximum and the lowest temperature that can be expected at the PV installation site are necessary for the strings design (according to IEC 60364-7-712).
The temperatures of the solar cells depend on the selected mounting system and on the ambient temperature. For tilt angle ground mounted installation ΔT between ambient e cell temperature is +30 °C.
The maximum ambient temperature in the PV installation site near to Rome is estimated (according to weather databases) 31 °C; then the maximum cell temperature that shall be used for the string sizing in the ground mounted PV installation is 61 °C.
The minimum ambient temperature in the PV installation site near to Rome is estimated (according to weather databases) -3 °C; then the minimum cell temperature that shall be used for the string sizing in the ground mounted PV installation is -3 °C.

B.1.3 PV module type selection

In order to size the PV field according to the land availability, the PV module type shall be selected.

—
Figure 85
PV module data

PV MODULE DATA			
Verify the specifications of the panel in the database and compare them with the correct data sheet If your panel is not present, you can manually edit the specifications ("Edit" button) to complete the configuration and the amendment of the panel is not saved in the database, but it is valid only for the session in progress.			
Manufacturer:	PV Module manufacturer A	Edit	
Model:	300W PV module – 60 monocrystalline cells		
Nominal Power [W]:	300	Grounding:	N/D
Open Circuit Voltage - Voc [V]:	40.10	Short Circuit Current - Isc [A]:	9.72
Max Power Voltage - Vmp [V]:	32.60	Max Power Current - Imp [A]:	9.21
Temperature coeff. Voc [V/°C]:	-0.12	Temperature coeff. Isc [mA/°C]:	4.61
Temperature coeff. Voc [%/°C]:	-0.299	Temperature coeff. Isc [%/°C]:	0.047
Max.Sys.Volt (IEC) [V]:	1500	Temperature coeff. Pmax [%/°K]:	-0.39



— Figure 86 dimensions of the selected module type

Determining the PV module max V_{OC} (according to IEC 60364-7-712)
The maximum open circuit voltage ($V_{OC\ MAX}$) of the selected PV module (60 monocrystalline 6” cells rated 300W at STC) is 40.10 V at STC.
The minimum ambient temperature in Rome (Italy) is -3 °C.
The voltage temperature coefficient (β) of the above PV module is -0.299 [%/K].

— Equation 80

$$V_{OC\ MAX} = 40.10 \cdot \left[1 + (-0.299\%) \cdot \left((-3) - 25\right)\right] = 40.10 \cdot [1 - 0.00299 \cdot (-3 - 25)]$$
$$V_{OC\ MAX} = 40.10 \cdot [1 + 0.00299 \cdot 28] = 43.45\ V$$

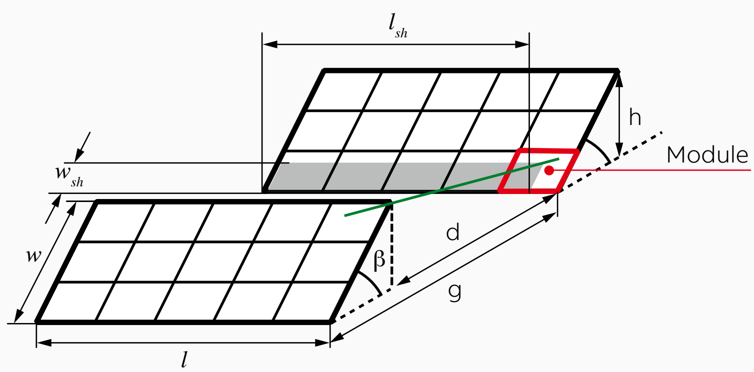
Determining the PV module min V_{MPP}
The minimum MPP voltage ($V_{MPP\ min}$) of the selected PV module (60 monocrystalline 6” cells rated 300W at STC) is 32.60 V.
The maximum ambient temperature in Rome (Italy) is 31 °C and then the maximum cell temperature that shall be used for the string sizing in the ground mounted PV installation is 61 °C.
The voltage temperature coefficient (β) of the above PV module is -0.299 [%/K].

— Equation 81

$$V_{MPP\ min} = 32.6 \cdot [1 + (-0.299\%) \cdot (61 - 25)] = 32.6 \cdot [1 - 0.00299 \cdot (36)]$$
$$V_{MPP\ min} = 32.6 \cdot [1 - 0.00299 \cdot 36] = 29.09\ V$$

B.1.4 Array physical configurations

During the design phase, the self-shading effects shall be considered in the ground-mounted PV system with fix free standing PV arrays. The self-shading losses are caused by a preceding row of PV modules and it applies to all but the first row of PV modules. With a careful planning the self-shading losses can be reduced to a minimum. PV designer use different assumptions to define the minimal distance d between neighbouring rows.



— Figure 87 distance between neighbouring rows – row spacing

INDEX

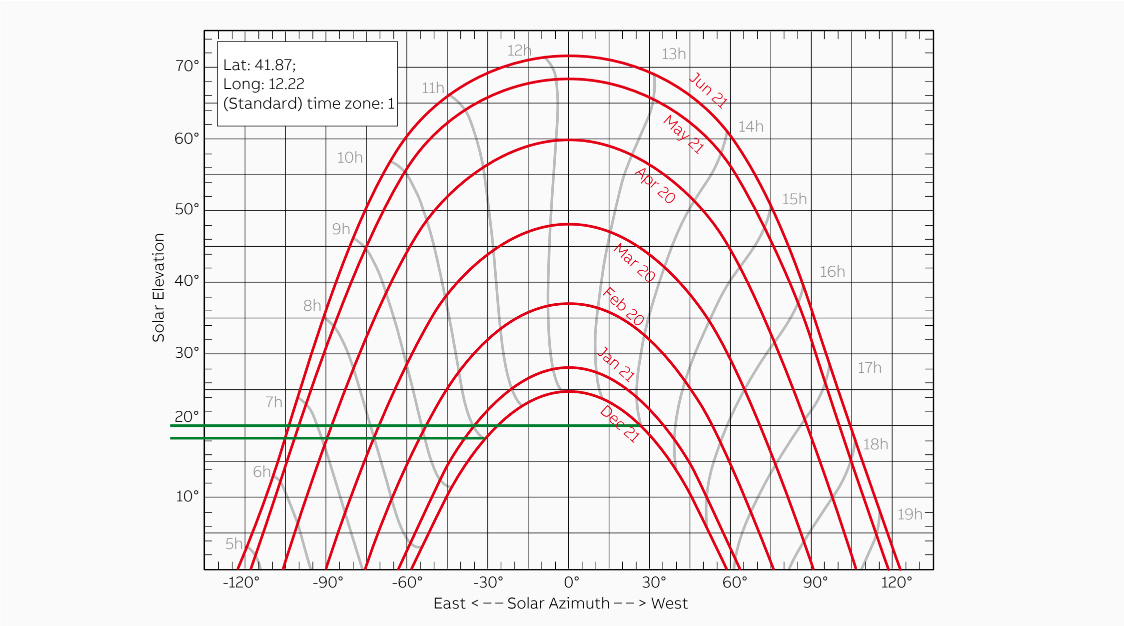
In order to calculate the inter-row spacing (d) for your panel, it is necessary to calculate the height difference (h) from the back of the module to the surface. To do that, follow this calculation below:

—
Equation 82

$$h = w \cdot \sin\beta$$

The height difference strictly depends from the PV module positioning in the panel.
Another parameter necessary to calculate the row spacing is the sun elevation. In order to avoid shading between 10:00 AM and 2:00 PM on December 21 (winter solstice) at a module inclination angle, the sun elevation could be identified by the sun path charts in Cartesian coordinates (Figure 88).

—
Figure 88
sun path in latitude 41.871730 and latitude 12.217600



At 10:00 AM, in the place of the PV installation, the sun elevation (θ) is around 18°. At 2:00 PM, in the place of the PV installation, the sun elevation (θ) is around 20°. The minimum elevation is 18°.
Then the panels row spacing is:

—
Equation 83

$$d = h / \tan\theta$$

In case the panel tilted 34° is composed by 2 modules in portrait condition

—
Figure 89
panel of PV module in portrait conditions

The width of the panel is:

—
Equation 84

$$w = 2 \cdot h_{module} = 2 \cdot 1.65\,m = 3.30\,m$$

the height difference is:

—
Equation 85

$$h = w \cdot \sin\beta = 3.30\,m \cdot \sin 34 = 1.84\,m$$

Then the panels row spacing is:

—
Equation 86

$$d = \frac{h}{\tan\theta} = \frac{1.84\,m}{\tan 18} = 5.66\,m$$

And the row width is:

—
Equation 87

$$g = d + w \cdot \cos\beta = 5.66\,m + 3.30\,m \cdot \cos 34 = 5.66\,m + 2.73\,m = 8.39\,m$$

In case the panel tilted 34° is composed by 3 modules in landscape condition

—
Figure 90
panel of PV module in landscape conditions

The width of the panel is:

—
Equation 88

$$w = 3 \cdot w_{module} = 3 \cdot 0.992\, m = 2.976\, m$$

the height difference is:

—
Equation 89

$$h = w \cdot \sin\beta = 2.976\, m \cdot \sin 34 = 1.66\, m$$

Then the panels row spacing is:

—
Equation 90

$$d = \frac{h}{\tan\theta} = \frac{1.66\, m}{\tan 18} = 5.10\, m$$

And the row width is:

—
Equation 91

$$g = d + w \cdot \cos\beta = 5.10\, m + 2.976\, m \cdot \cos 34 = 5.66\, m + 2.47\, m = 8.13\, m$$

According to these values and according to the actual PV module performance, the land occupation is around 15 m² / kW.
That means, considering the space for the cabins and the internal roads, in a 6.6 hectares land could be installed around 4.4 MW of monocrystalline PV modules.

9

B.1.5 Inverter size selection

The selection of the inverter and of its sizing is carried out according to the PV generator rated power. According to the available land (6.6 hectares) and according to the above land occupation, the PV generator rated power ($P_{DC\ PV\ GEN}$) is 4.4 MW. In order to use central inverters, the best option is to use 2 centralized inverters with a $P_{DC\ Max\ Inverter}$ =3.200 MW and $P_{AC\ Max\ Inverter}$ =2.2 MVA

—
Figure 91
Inverter data

Input (DC)	
Maximum recommended PV power ($P_{PV,\ max}$) 1)	3200 kWp
Maximum DC current ($I_{max\ (DC)}$)	2400 A
DC voltage range, mpp ($U_{DC,\ mpp}$) at 35 °C	935 to 1500 V
DC voltage range, mpp ($U_{DC,\ mpp}$) at 50 °C	935 to 1100 V
Maximum DC voltage ($U_{max\ (DC)}$)	1500 V
Number of MPPT trackers	1
Number of protected DC inputs	8 2) to 24 (+/-)
Output (AC)	
Maximum power ($S_{max\ (AC)}$) 3)	2200 kVA
Nominal power ($S_{N(AC)}$) 4)	2000 kVA
Maximum AC current ($I_{max\ (AC)}$)	1925 A
Nominal AC current ($I_{N(AC)}$)	1750 A
Nominal output voltage ($U_{N(AC)}$) 5)	660 V
Output frequency 5)	50/60 Hz
Harmonic distortion, current 6)	< 3%
Distribution network type 7)	TN and IT

Efficiency	
Maximum 8)	98.8%
Euro-eta 8)	98.6%
CEC efficiency 9)	98.5%
Power consumption	
Self consumption in normal operation	≤ 2500 W
Standby operation consumption	235 W
Auxiliary voltage source 10)	External, 1-phase

1) DC/AC ratio over 1.6 might decrease maintenance intervals
2) As standard
3) At 35 °C
4) At 50 °C
5) ±10%
6) At nominal power
7) Inverter side must be IT type
8) Without auxiliary power consumption at min U_{DC}
9) With auxiliary power included
10) Internal as option

B.1.6 Determining the Maximum Number of PV Modules per String

According to the above module maximum open circuit voltage at the minimum ambient temperature in Rome ($V_{OC\,MAX}$=43.45 V), the maximum number of PV modules connected in series that could be connected to the inverter is:

— Equation 92

$$N_{MAX\ Module} \leq \frac{V_{MAX\ Inverter}}{V_{OC\ MAX\ Module}} = \frac{1500}{43.45} = 34.52$$

The maximum system voltage of all the components of the PV system (combiner boxes, switch, connectors, cables, PV Modules, etc.) shall be compatible with the maximum input voltage of the inverter (1500 V).
The maximum system voltage of the selected PV modules is 1500 V and then the modules are compatible with the maximum input voltage of the inverter.

B.1.7 Determining the Minimum Number of PV Modules per String

In case the string voltage falls below the minimum MPP voltage of the inverter (935 V), MPP tracking is not possible or yield losses can occur. The minimum number of PV modules connected in series to assure that the string voltage at MPP condition is always above the minimum MPP voltage of the inverter is:

— Equation 93

$$N_{\min mod} \geq \frac{V_{\min MPPT\ Inverter}}{V_{MPP\ \min\ Module}} = \frac{935}{29.09} = 32.14$$

B.1.8 Number of PV Modules per String

The selected PV inverter is equipped with single MPPT.
The number of PV modules per string must:
- not exceed the Maximum Number of PV Modules per String (34);
- not be less than Minimum Number of PV Modules per String (33).

Determining the Maximum PV Module Current

— Equation 94

$$I_{SC\ OPC\ MAX\ Module} = I_{SC\ STC} \cdot [1 - \alpha \cdot (25 - T_{cell})] = 9.72 \cdot [1 - 0.00047 \cdot (25 - 61)] = 9.88\ A$$

Determining the Maximum PV string Current

— Equation 95

$$I_{SC\ OPC\ MAX\ Module} = I_{SC\ OPC\ MAX\ string} = 9.88\ A$$

Determining the String Number
The maximum number of strings connectable to the single MPPT is:

— Equation 96

$$N_{MAX\ string} \leq \frac{I_{Max\ input}}{I_{SC\ OPC\ MAX\ string}} = \frac{2400}{9.88} = 242.91$$

B.1.9 Definitive inverter layout

In order to optimize the cabling of the modules, is a best practice to consider the array physical configurations (panel configuration) in the selection of string dimensions.

Option 1
The PV field is divided in 2 equal sub-systems; each sub-system is equipped with 1 inverter. In case the panel is composed by 2 modules in portrait condition, in order to maximize the power connected, the best stringing option is:
- 216 strings of 34 PV modules connected to inverter 1 (2203.2 kW);
- 216 strings of 34 PV modules connected to inverter 2 (2203.2 kW);

According to this configuration the total power of the PV field is 4.4064 MW.

Option 2
The PV field is divided in 2 equal sub-systems; each sub-system is equipped with 1 inverter. In case the panel is composed by 3 modules in landscape condition, in order to maximize the power connected, the best stringing option is:
- 224 strings of 33 PV modules connected to inverter 1 (2217.6 kW);
- 224 strings of 33 PV modules connected to inverter 2 (2217.6 kW);

According to this configuration the total power of the PV field is 4.4352 MW.

B.1.10 DC Combiner boxes

The connection of modules in series is made on the modules themselves, while the parallel connection of the strings is made inside combiner boxes that accommodate, along with the interconnection systems, also the overcurrent protection devices, disconnectors and surge protection devices.
The combiner boxes form subsystems that can be standardized according to the number of strings, voltage and rated current.

Option 1
Each one of the sub-systems is composed by 216 string of 34 PV modules. The 216 strings are connected in 4 groups of 54 strings.
In any case the 54 strings could be connected to 4 combiner boxes equipped with 16 strings input (13 or 14 strings input will be used). In the combiner box selection should be considered:
- The maximum system voltage of all components shall be compatible with the maximum input voltage of the PV field. In this case the maximum system voltage shall be 1500 V;
- The disconnector conventional free-air thermal current (Ith) shall be compatible with the maximum current of the connected strings. In this case 14 strings are connected and then:

— Equation 97

$$I_{th} > 14 \cdot I_{SC\ MAX\ string} = 14 \cdot 9.88\ \text{A} = 138.32\ \text{A}$$

- The combiner box shall be equipped with type 1 SPDs;
- The fuses installed in the fuse holders[40] shall be gPV fuses with a maximum current In;

— Equation 98

$$1.5 \cdot I_{sc} \leq I_n < 2.4 \cdot I_{sc}$$

— Equation 99

$$1.5 \cdot 9.72\ A \leq I_n < 2.4 \cdot 9.72\ A$$

— Equation 100

$$14.58\ A \leq I_n < 23.32\ A$$

Moreover, the PV module datasheet report that Maximum series fuse rating of the modules is 15 A.

— Equation 101

$$I_n < I_{rev\ module} = 15\ A$$

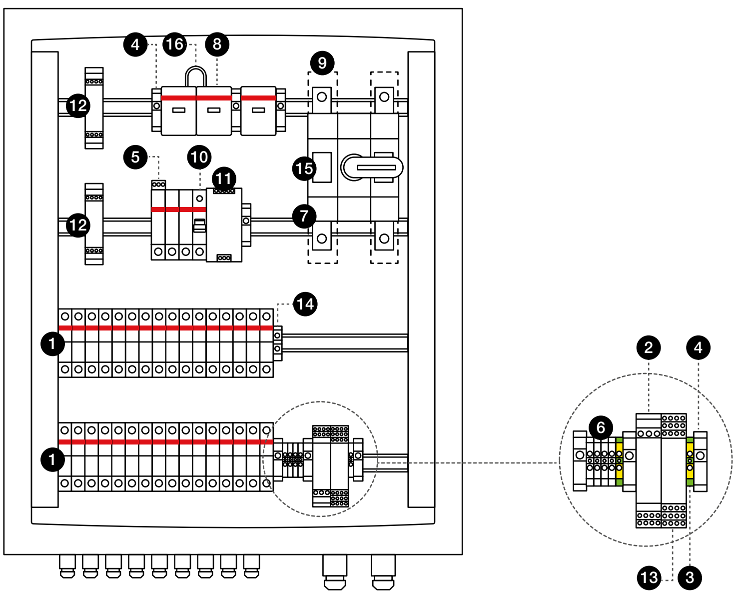
—
40
The current carrying capacity of the string cables is higher than the maximum current which can pass through them under standard operating conditions; therefore, it is not necessary to protect them against overload. Usually it is not necessary to protect PV string cables against overloads if they will be chosen with a current carrying capacity equal to or greater than 1.25 times the I_{sc}. By the way, in case of a lot of strings connected in parallel, the cables and the string connectors must be protected against the short-circuit when their current carrying capacity is lower than I_{sc2}. $1.25 \cdot I_{sc} \leq I_{z\ string} < I_{sc2} = 1.25 \cdot (S_A - 1) \cdot I_{sc}$ Where S_A is the number of the string of the sub-array. In any case the use of the fuse holders with fuses is recommendable to disconnect (not under load) the strings in case of maintenance operations.

—
Figure 92
16 strings 1500 V DC
with monitoring system

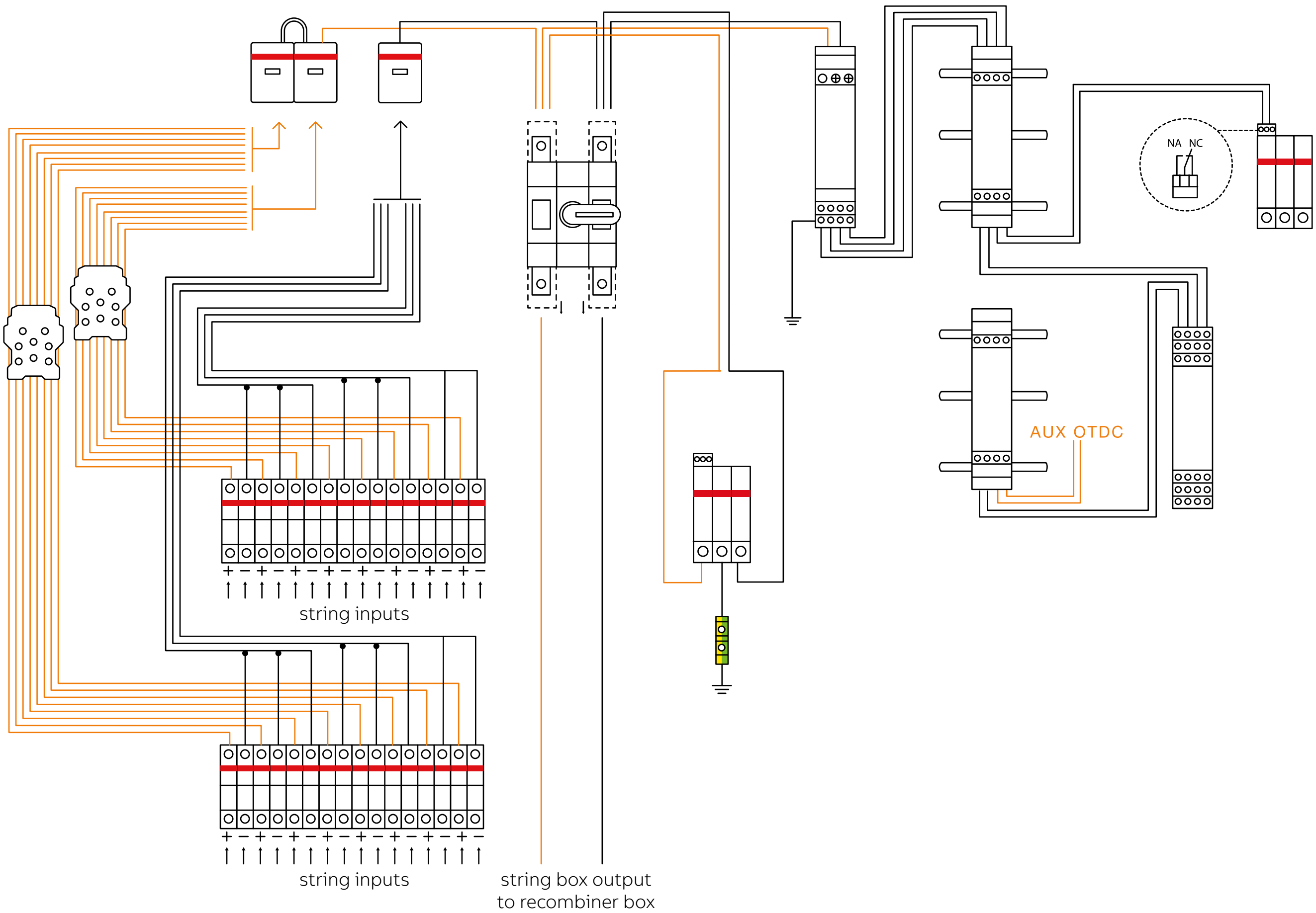
The gPV fuses maximum current shall be then 15 A.

The combiner box diagram is indicated in Figure 92.

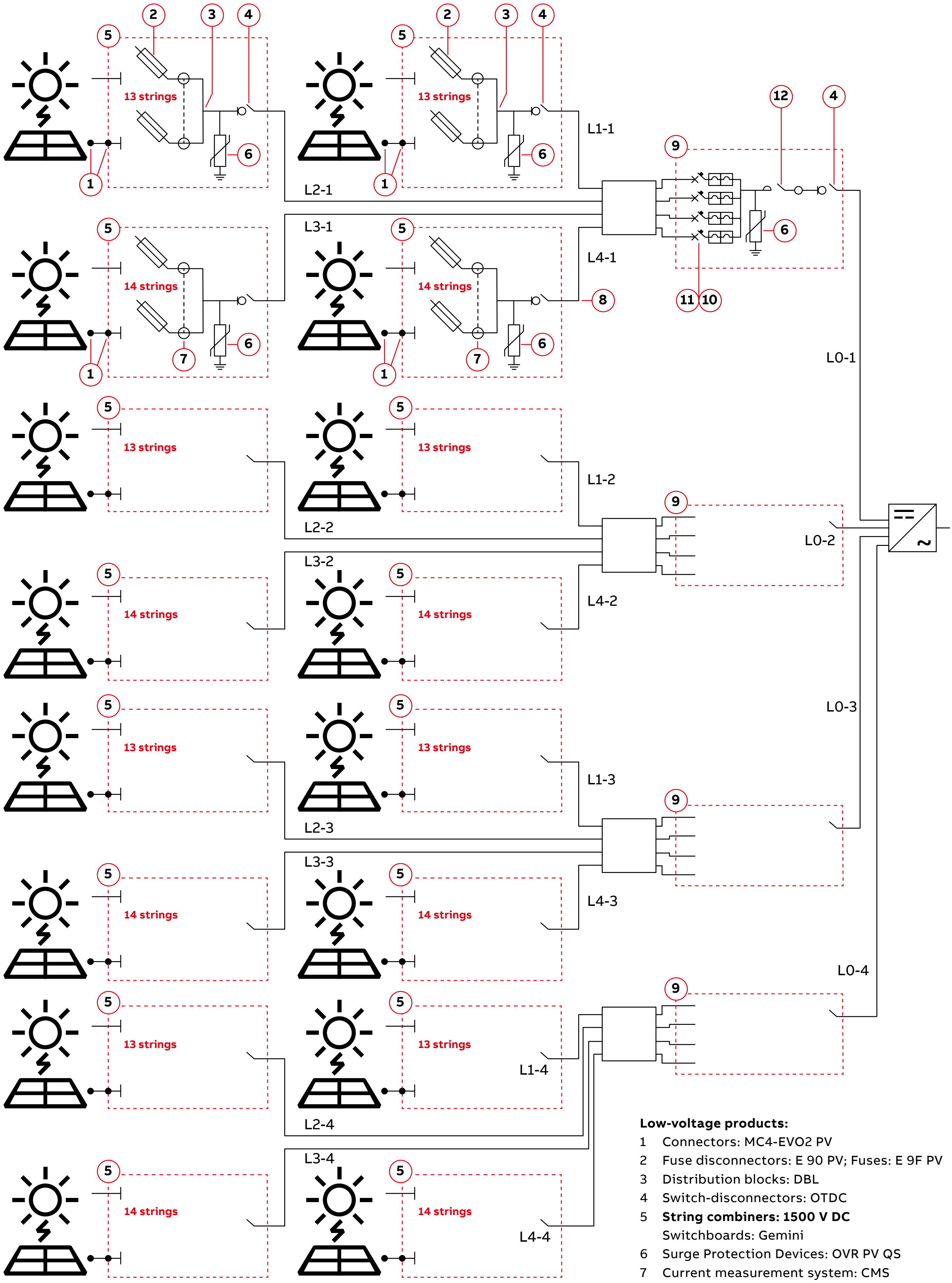
16 strings, 1500 V DC with monitoring



1 Fuse holder E90PV
2 Voltage monitor
3 Terminal block M4 PE
4 Stop BAM3
5 Surge protection OVR PV
6 Terminal block M4 GREY
7 Switch disconnector OTDC250E11K
8 Distribution block DBL175
9 Shroud for OTDC
10 Switch E211
11 Power supply CP-E 2,5 24V
12 Current monitor
13 Communication device
14 Terminal block M35 PE
15 Aux contact OTDC (special accessory)
16 Link



The diagram of connection of the combiner boxes of each subsystem is indicated in Figure 93 (next page).



Low-voltage products:
1 Connectors: MC4-EVO2 PV
2 Fuse disconnectors: E 90 PV; Fuses: E 9F PV
3 Distribution blocks: DBL
4 Switch-disconnectors: OTDC
5 **String combiners: 1500 V DC**
Switchboards: Gemini
6 Surge Protection Devices: OVR PV QS
7 Current measurement system: CMS
8 String Monitoring Controller
9 Recombiner
10 Moulded Case Circuit-Breakers: Tmax PV
11 Insulation monitoring devices: CM-IWx
12 Contactors: GAF Series

—
Figure 93
diagram of DC side of each subsystem: 216 string of 34 PV modules

Option 2

Each one of the sub-systems is composed by 224 string of 33 PV modules. The 224 strings are connected in 4 groups of 56 strings.
In any case the 56 strings could be connected to 4 combiner boxes equipped with 16 strings input (14 strings input will be used). In the combiner box selection should be considered:

- The maximum system voltage of all components shall be compatible with the maximum input voltage of the PV field. In this case the maximum system voltage shall be 1500 V;
- The disconnector conventional free-air thermal current (Ith) shall be compatible with the maximum current of the connected strings. In this case 14 strings are connected and then:

Equation 102

$$I_{th} > 14 \cdot I_{SC\,MAX\,string} = 14 \cdot 9.88\ \mathrm{A} = 138.32$$

- The combiner box shall be equipped with type 1 SPDs;
- The fuses installed in the fuse holders[41] shall be gPV fuses with a maximum current I_n;

Equation 103

$$1.5 \cdot I_{sc} \leq I_n < 2.4 \cdot I_{sc}$$

Equation 104

$$1.5 \cdot 9.72\ A \leq I_n < 2.4 \cdot 9.72\ A$$

Equation 105

$$14.58\ A \leq I_n < 23.32\ A$$

Moreover, the PV module datasheet report that Maximum series fuse rating of the modules is 15 A.

Equation 106

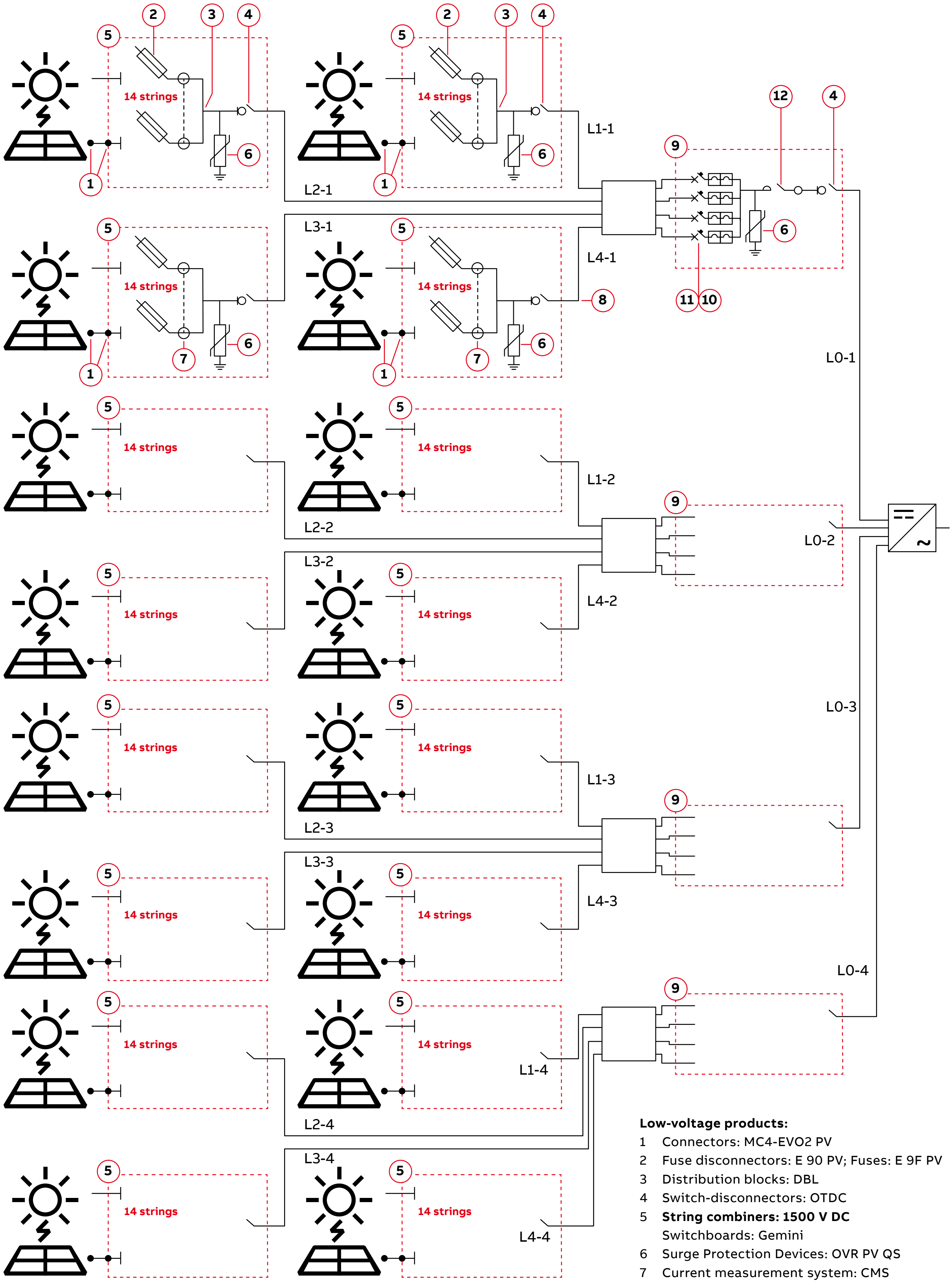
$$I_n < I_{rev\,module} = 15\ A$$

The gPV fuses maximum current shall be then 15 A.

The combiner box diagram is indicated in Figure 94.

The diagram of interconnection of the combiner boxes of each subsystem is indicated in Figure 94 (next page)

41
The current carrying capacity of the string cables is higher than the maximum current which can pass through them under standard operating conditions; therefore, it is not necessary to protect them against overload. Usually it is not necessary to protect PV string cables against overloads if they will be chosen with a current carrying capacity equal to or greater than 1.25 times the I_{sc}. By the way, in case of a lot of strings connected in parallel, the cables and the string connectors must be protected against the short-circuit when their current carrying capacity is lower than I_{sc2}. $1.25 \cdot I_{sc} \leq I_{z\,string} < I_{sc2} = 1.25 \cdot (S_A - 1) \cdot I_{sc}$ Where S_A is the number of the string of the sub-array. In any case the use of the fuse holders with fuses is recommendable to disconnect (not under load) the strings in case of maintenance operations.



Low-voltage products:

1 Connectors: MC4-EVO2 PV
2 Fuse disconnectors: E 90 PV; Fuses: E 9F PV
3 Distribution blocks: DBL
4 Switch-disconnectors: OTDC
5 **String combiners: 1500 V DC**
Switchboards: Gemini
6 Surge Protection Devices: OVR PV QS
7 Current measurement system: CMS
8 String Monitoring Controller
9 Recombiner
10 Moulded Case Circuit Breakers: Tmax PV
11 Insulation monitoring devices: CM-IWx
12 Contactors: GAF Series

—
Figure 94
diagram of DC side of each subsystem: 224 string of 33 PV modules

B.1.11 Choice of string cables

The installation is in Europe and then the cable shall respect the European coding for solar cables: the cables shall be H1Z2Z2-K.

Option 1

Considering that:

- the maximum open circuit voltage ($V_{OC\ MAX}$) of the selected PV module (60 monocrystalline 6" cells rated 300W at STC) is 40.10 V at STC;
- the maximum open circuit voltage ($V_{OC\ MAX}$) at lower temperature is 43.45 V;
- the strings are composed by 34 modules;

the maximum string open circuit voltage ($V_{OC\ MAX\ string}$) at lower temperature is 1477.3 V.
The cables voltage rating shall be chosen according to the maximum open circuit voltage ($V_{OC\ MAX\ string}$) and then > 1477.3 V.
The string cables shall be selected in order to maintain the voltage drop < 2 %.

Considering that:

- string cables will be disposed in perforated metal cable tray on the back side of the structures;
- in the same duct will put around 6 couple of string cables;
- the average length of the string circuit is 150 m;

the following solar cable is selected for the strings:
cable type: H1Z2Z2-K
cross section: 4 mm^2
Rated voltage DC: 1.5 kV
Ambient temperature in operation: -40 °C up to +90 °C
I_0 Current carrying capacity for single cable free in air: 55 A
Max. short-circuit temperature of the conductor: 250 °C (5 s.)

The continuous current-carrying capacity I_z shall be verified and it shall be:

—
Equation 107

$$I_z \geq I_{sc\ MAX\ string} = I_{SC\ STC\ string} \cdot 1.25$$

The Maximum PV string Current, for cable dimensioning, is $I_{SC\ MAX\ string}$ = 12.15 A.
According to this, the continuous current-carrying capacity Iz of the PV string cables, for wire sizing, shall be:

—
Equation 108

$$I_z \geq 12.15\ A$$

The current carrying capacity I_z of the solar cables disposed in perforated metal cable tray at the operating temperature of 70 °C results according to IEC 60364-5-52 is I_z= 36.53 A.
The carrying capacity is greater than 1.25 times the I_{sc} of the string; then cables dimensioning is correct[42] and it is not necessary to protect PV string cables against overloads.
By the way, considering the number of strings connected in parallel in the sub-arrays (S_A), the string cable didn't verify the condition

—
42
Ref. to paragraph 6.1.1

—
Equation 109

$$I_{z\ string} < 1.25 \cdot (S_A - 1) \cdot I_{sc}$$

Therefore, the cables and the string connectors must be protected against the short-circuit using fuses in the single string input of the combiner box.
According to the fuses time current characteristics, shall be verified that (I^2t) of the fuses, maximum fuses specific energy, is less equal than ≤ (K^2S^2) of the cables, maximum value of specific energy that the cable is able to withstand.
Moreover, the contribution to short-circuit on the DC side of the inverter may come from the grid and from the discharge of the capacitors inside the inverter (ref. to 6.1.3). Due to inverter constructive typology, it includes at least one blocking diode which prevents the grid current from contributing to the short-circuit.

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Option 2

Considering that:

- the maximum open circuit voltage ($V_{OC\ MAX}$) of the selected PV module (60 monocrystalline 6” cells rated 300W at STC) is 40.10 V at STC;
- the maximum open circuit voltage ($V_{OC\ MAX}$) at lower temperature is 43.45 V;
- the strings are composed by 33 modules;

the maximum string open circuit voltage ($V_{OC\ MAX\ string}$) at lower temperature is 1433.85 V.
The cables voltage rating shall be chosen according to the maximum open circuit voltage ($V_{OC\ MAX\ string}$) and then > 1433.85 V.
The string cables shall be selected in order to maintain the voltage drop < 2 %.

Considering that:

- string cables will be disposed in perforated metal cable tray on the back side of the structures;
- in the same duct will put around 6 couple of string cables;
- the average length of the string circuit is 150 m;

the following solar cable is selected for the strings:
cable type: H1Z2Z2-K
cross section: 4 mm^2
Rated voltage DC: 1.5 kV
Ambient temperature in operation: -40 °C up to +90 °C
I_0 Current carrying capacity for single cable free in air: 55 A
Max. short-circuit temperature of the conductor: 250 °C (5 s.)

The continuous current-carrying capacity I_z shall be verified and it shall be:

Equation 110

$$I_z \geq I_{sc\ MAX\ string} = I_{SC\ STC\ string} \cdot 1.25$$

The Maximum PV string Current, for cable dimensioning, is $I_{SC\ MAX\ string}$ = 12.15 A.
According to this, the continuous current-carrying capacity I_z of the PV string cables, for wire sizing, shall be:

Equation 111

$$I_z \geq 12.15\ A$$

The current carrying capacity I_z of the solar cables disposed in perforated metal cable tray at the operating temperature of 70 °C results according to IEC 60364-5-52 is I_z= 36.53 A.
The carrying capacity is greater than 1.25 times the I_{sc} of the string; then cables dimensioning is correct[43] and it is not necessary to protect PV string cables against overloads.
By the way, considering the number of strings connected in parallel in the sub-arrays (S_A), the string cable didn’t verify the condition

43 Ref. to paragraph 6.1.1

Equation 112

$$I_{z\ string} < 1.25 \cdot (S_A - 1) \cdot I_{sc}$$

Therefore, the cables and the string connectors must be protected against the short-circuit using fuses in the single string input of the combiner box.
According to the fuses time current characteristics, shall be verified that (I^2t) of the fuses, maximum fuses specific energy, is less or equal than ≤ (K^2S^2) of the cables, maximum value of specific energy that the cable is able to withstand.
Moreover, the contribution to short-circuit on the DC side of the inverter may come from the grid and from the discharge of the capacitors inside the inverter (ref. to 6.1.3). Due to inverter constructive typology, it includes at least one blocking diode which prevents the grid current from contributing to the short-circuit.

B.1.12 DC recombiner boxes

The parallel connection of the cables that come from the combiner boxes is made inside recombiner boxes that accommodate, along with the interconnection systems, also the overcurrent protection devices, disconnectors and surge protection devices.

Option 1
As shown in Figure 93 the recombiner box contain:
- Moulded case circuit-breaker to obtain overcurrent protection; the disconnector rated service current (I_n) shall be compatible with the maximum current of the connected strings.
  In this case 13 or 14 strings are connected to each one of the sub systems; then in case of 14 strings:

Equation 113
$$1.25 \cdot S_{SA} \cdot I_{sc} \leq I_n < 2.4 \cdot S_A \cdot I_{sc}$$
Equation 114
$$1.25 \cdot 14 \cdot 9.72\ \text{A} \leq I_n < 2.4 \cdot 14 \cdot 9.72\text{A}$$
Equation 115
$$170.1\ \text{A} \leq I_n < 326.6\ \text{A}$$

- type 1 SPDs;
- contactor for remote disconnection (it is an optional; it could be required for an advance safety system);
- Switch disconnector: the disconnector conventional free-air thermal current (I_{th}) shall be compatible with the maximum current of the connected strings. In this case 54 strings are connected to the subsystem and then:

Equation 116
$$I_{th} > 54 \cdot I_{SC\ MAX\ string} = 54 \cdot 9.88\ \text{A} = 533.52\ \text{A}$$

In the recombiner box selection should be considered the maximum system voltage of all components shall be compatible with the maximum input voltage of the PV field. In this case the maximum system voltage shall be 1500 V.

Option 2
As shown in Figure 94 the recombiner box contain:
- Moulded case circuit-breaker to obtain overcurrent protection; the disconnector rated service current (I_n) shall be compatible with the maximum current of the connected strings.
  In this case 14 strings are connected to each one of the sub systems and then:

Equation 117
$$1.25 \cdot S_{SA} \cdot I_{sc} \leq I_n < 2.4 \cdot S_A \cdot I_{sc}$$
Equation 118
$$1.25 \cdot 14 \cdot 9.72\ \text{A} \leq I_n < 2.4 \cdot 14 \cdot 9.72\text{A}$$
Equation 119
$$170.1\ \text{A} \leq I_n < 326.6\ \text{A}$$

- type 1 SPDs;
- contactor for remote disconnection (it is an optional; it could be required for an advance safety system);
- Switch disconnector: the disconnector conventional free-air thermal current (I_{th}) shall be compatible with the maximum current of the connected strings. In this case 56 strings are connected to the subsystem and then:

Equation 120
$$I_{th} > 56 \cdot I_{SC\ MAX\ string} = 56 \cdot 9.88\ \text{A} = 553.28\ \text{A}$$

In the recombiner box selection should be considered the maximum system voltage of all components shall be compatible with the maximum input voltage of the PV field. In this case the maximum system voltage shall be 1500 V.

B.1.13 Choice cables between combiner boxes and recombiner boxes

The connection of the PV array combiner box to the recombiner box is carried out by using two single-core cables H1Z2Z2-K.
The length of the cables between combiner boxes and recombiner boxes is indicated in Table 7.

Table 7
length of cable for option 1 and option 2

Line	Circuit length [m]	Line	Circuit length [m]
L1-1	100	L1-3	100
L2-1	140	L2-3	140
L3-1	140	L3-3	140
L4-1	100	L4-3	100
L1-2	60	L1-4	60
L2-2	60	L2-4	60
L3-2	60	L3-4	60
L4-2	60	L4-4	60

Option 1
Considering that the maximum string open circuit voltage ($V_{OC\ MAX\ string}$) at lower temperature is 1477.3 V, the cables voltage rating shall be chosen according to the maximum open circuit voltage ($V_{OC\ MAX\ string}$) and then > 1477.3 V. The cables shall be selected in order to maintain the voltage drop < 2 % and in order to verify the current carrying capacity.

Considering that:
- cables will be disposed in cable ducting in the ground;
- in the same duct will put only a circuit (2 cables);

the following solar cable is selected for the strings:
cable type: H1Z2Z2-K
Rated voltage DC: 1.5 kV
Ambient temperature in operation: -40 °C up to +90 °C
Max. short-circuit temperature of the conductor: 250 °C (5 s.)

Table 8
length of cable & cross section for option 1 and option 2

Line	Circuit length [m]	Cross section [mm²]	Line	Circuit length [m]	Cross section [mm²]
L1-1	100	35	L1-3	100	35
L2-1	140	50	L2-3	140	50
L3-1	140	50	L3-3	140	50
L4-1	100	35	L4-3	100	35
L1-2	60	25	L1-4	60	25
L2-2	60	25	L2-4	60	25
L3-2	60	25	L3-4	60	25
L4-2	60	25	L4-4	60	25

The continuous current-carrying capacity I_z shall be verified and it shall be:

Equation 121
$$I_z \geq I_{sc\ MAX\ string} = I_{SC\ STC\ string} \cdot 1.25$$

The Maximum PV string Current, for cable dimensioning, is $I_{SC\ MAX\ string}$ = 12.15 A.
According to this, the continuous current-carrying capacity I_z of the PV string cables, for wire sizing, shall be:

Equation 122
$$I_z \geq 12.15\ A$$

Each combiner box is connected with at least 14 strings.
According to this, the continuous current-carrying capacity I_z of cables, for wire sizing, shall be:

Equation 123
$$I_z \geq 12.15 \cdot 14 = 170.1\ \text{A}$$

The current carrying capacity I_z of the solar cables calculated according to IEC 60364-5-52 is verified.

It is not necessary to protect the PV array cables against overloads they are chosen with a current carrying capacity equal to or greater than 1.25 times the sum of the I_{sc} of the sub-array strings.
By the way, considering the number of strings connected in parallel in the sub-arrays (S_A), the string cable didn't verify the condition

—
Equation 124

$$I_{z\ sub-array} < 1.25 \cdot (S_A - S_{SA}) \cdot I_{sc}$$

Where S_{SA} is the number of parallel-connected PV strings in the PV sub-array.
Therefore, the between combiner boxes and recombiner boxes must be protected against the short-circuit using moulded case circuit-breakers in each input of the recombiner box.
According to the fuses time current characteristics, shall be verified that (I^2t) of the fuses, maximum fuses specific energy, is less or equal than ≤ (K^2S^2) of the cables, maximum value of specific energy that the cable is able to withstand.

Option 2
Considering that the maximum string open circuit voltage ($V_{OC\ MAX\ string}$) at lower temperature is 1433.85 V, the cables voltage rating shall be chosen according to the maximum open circuit voltage ($V_{OC\ MAX\ string}$) and then > 1433.85 V.
The cables shall be selected in order to maintain the voltage drop < 2 % and in order to verify the current carrying capacity.

Considering that:
- cables will be disposed in cable ducting in the ground;
- in the same duct will put only a circuit (2 cables);

the following solar cable is selected for the strings:
cable type: H1Z2Z2-K
Rated voltage DC: 1.5 kV
Ambient temperature in operation: -40 °C up to +90 °C
Max. short-circuit temperature of the conductor: 250 °C (5 s.)

—
Table 9
length of cable & cross section for option 1 and option 2

Line	Circuit length [m]	Cross section [mm²]	Line	Circuit length [m]	Cross section [mm²]
L1-1	100	35	L1-3	100	35
L2-1	140	50	L2-3	140	50
L3-1	140	50	L3-3	140	50
L4-1	100	35	L4-3	100	35
L1-2	60	25	L1-4	60	25
L2-2	60	25	L2-4	60	25
L3-2	60	25	L3-4	60	25
L4-2	60	25	L4-4	60	25

—
Equation 125

$$I_z \geq I_{sc\ MAX\ string} = I_{SC\ STC\ string} \cdot 1.25$$

The Maximum PV string Current, for cable dimensioning, is $I_{SC\ MAX\ string}$ = 12.15 A. According to this, the continuous current-carrying capacity I_z of the PV string cables, for wire sizing, shall be:

—
Equation 126

$$I_z \geq 12.15\ A$$

Each combiner box is connected with at least 14 strings.
According to this, the maximum continuous current-carrying capacity I_z of cables, for wire sizing, shall be:

—
Equation 127

$$I_z \geq 12.15 \cdot 14 = 170.1\ \text{A}$$

The current carrying capacity I_z of the solar cables calculated according to IEC 60364-5-52 is verified.
It is not necessary to protect the PV array cables against overloads they are chosen with a current carrying capacity equal to or greater than 1.25 times the sum of the I_{sc} of the sub-array strings.
By the way, considering the number of strings connected in parallel in the sub-arrays (S_A), the string cable didn't verify the condition

—
Equation 128

$$I_{z\ sub-array} < 1.25 \cdot (S_A - S_{SA}) \cdot I_{sc}$$

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Where S_{SA} is the number of parallel-connected PV strings in the PV sub-array.
Therefore, the between combiner boxes and recombiner boxes must be protected against the short-circuit using moulded case circuit-breakers in each input of the recombiner box.
According to the fuses time current characteristics, shall be verified that (I^2t) of the fuses, maximum fuses specific energy, is less or equal than ≤ (K^2S^2) of the cables, maximum value of specific energy that the cable is able to withstand.

B.1.14 Choice cables between recombiner boxes and inverter

The connection of the PV array combiner box to the recombiner box is carried out by using two single-core cables H1Z2Z2-K.
The length of the cables between combiner boxes and recombiner boxes is indicated in Table 10.

—
Table 10
length of cable for option 1 and option 2

Line	Circuit length [m]
L0-1	100
L0-2	20
L0-3	100
L0-4	20

Option 1
Considering that the maximum string open circuit voltage ($V_{OC\ MAX\ string}$) at lower temperature is 1477.3 V, the cables voltage rating shall be chosen according to the maximum open circuit voltage ($V_{OC\ MAX\ string}$) and then > 1477.3 V.
The cables shall be selected in order to maintain the voltage drop < 2 % and in order to verify the current carrying capacity.

Considering that:
- cables will be disposed in cable ducting in the ground;
- in the same duct will put only a circuit (2 cables);

the following solar cable is selected for the strings:
cable type: H1Z2Z2-K
Rated voltage DC: 1.5 kV
Ambient temperature in operation: -40 °C up to +90 °C
Max. short-circuit temperature of the conductor: 250 °C (5 s.)

—
Table 11
length of cable & cross section for option 1 and option 2

Line	Circuit length [m]	Cross section [mm²]
L0-1	100	240
L0-2	20	240
L0-3	100	240
L0-4	20	240

—
Equation 129

$$I_z \geq I_{sc\ MAX\ string} = I_{SC\ STC\ string} \cdot 1.25$$

The Maximum PV string Current, for cable dimensioning, is $I_{SC\ MAX\ string}$ = 12.15 A. According to this, the continuous current-carrying capacity I_z of the PV string cables, for wire sizing, shall be:

—
Equation 130

$$I_z \geq 12.15\ A$$

Each combiner box is connected with 15 strings.
Each recombiner box connect 4 combiner boxes.
According to this, the continuous current-carrying capacity I_z of cables, for wire sizing, shall be:

—
Equation 131

$$I_z \geq 12.15 \cdot (14 + 14 + 13 + 13) = 656.1\ \text{A}$$

The current carrying capacity I_z of the solar cables calculated according to IEC 60364-5-52 is verified.
It is not necessary to protect the PV array cables against overloads they are chosen with a current carrying capacity equal to or greater than 1.25 times the sum of the I_{sc} of the array strings.

Option 2

Considering that the maximum string open circuit voltage ($V_{OC\ MAX\ string}$) at lower temperature is 1433.85 V. the cables voltage rating shall be chosen according to the maximum open circuit voltage ($V_{OC\ MAX\ string}$) and then > 1433.85 V.

The cables shall be selected in order to maintain the voltage drop < 2 % and in order to verify the current carrying capacity.

Considering that:

- cables will be disposed in cable ducting in the ground;
- in the same duct will put only a circuit (2 cables);

the following solar cable is selected for the strings:
cable type: H1Z2Z2-K
Rated voltage DC: 1.5 kV
Ambient temperature in operation: -40 °C up to +90 °C
Max. short-circuit temperature of the conductor: 250 °C (5 s.)

—
Table 12
length of cable & cross section for option 1 and option 2

Line	Circuit length [m]	Cross section [mm²]
L0-1	100	240
L0-2	20	240
L0-3	100	240
L0-4	20	240

—
Equation 132

$$I_z \geq I_{sc\ MAX\ string} = I_{SC\ STC\ string} \cdot 1.25$$

The Maximum PV string Current, for cable dimensioning, is $I_{SC\ MAX\ string}$ = 12.15 A.
According to this, the continuous current-carrying capacity I_z of the PV string cables, for wire sizing, shall be:

—
Equation 133

$$I_z \geq 12.15\ A$$

3 combiner boxes are connected with 16 strings and 1 combiner box is connected with 15 strings.
According to this, the continuous current-carrying capacity I_z of cables, for wire sizing, shall be:

—
Equation 134

$$I_z \geq 12.15 \cdot (14 + 14 + 14 + 14) = 680.4\ \mathrm{A}$$

The current carrying capacity I_z of the solar cables calculated according to IEC 60364-5-52 is verified.
It is not necessary to protect the PV array cables against overloads they are chosen with a current carrying capacity equal to or greater than 1.25 times the sum of the I_{sc} of the array strings.

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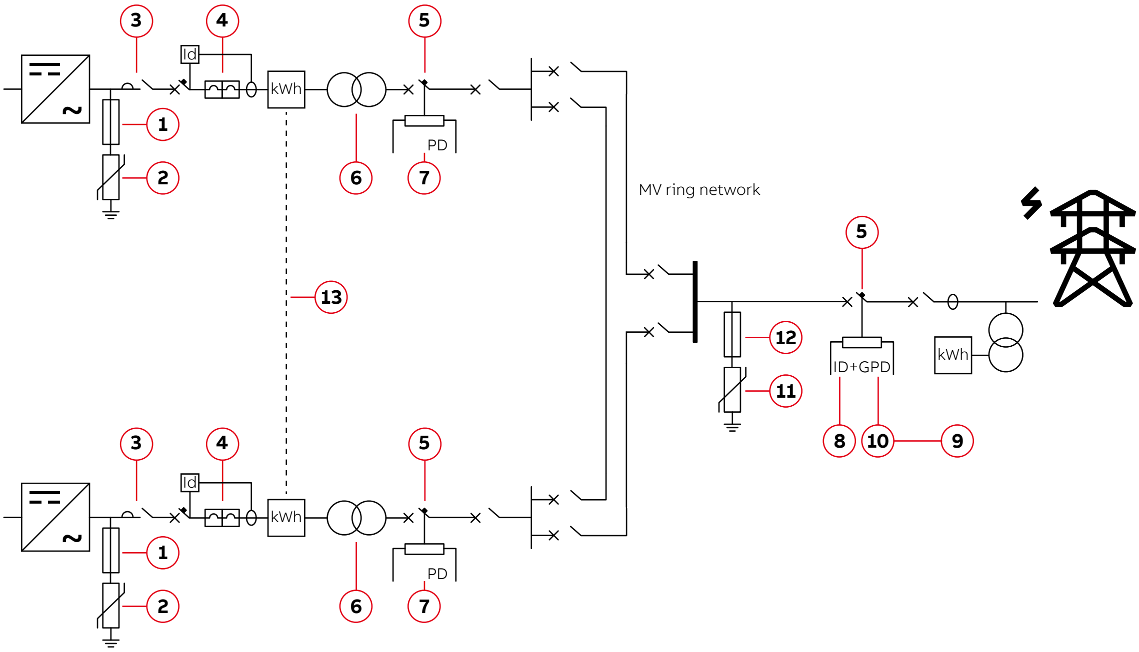
B.1.15 AC side

The diagram of AC side is indicated in Figure 95.



—
Figure 95
diagram of AC side

1 Fuse disconnectors: E90
2 Surge protection devices: OVR T1 / T1-T2 / T2 QS
3 Contactors: AF Series
4 Moulded case circuit-breakers:
Tmax XT, Tmax T
Air circuit -breakers: Emax 2

Medium-voltage products:
5 Gas-insulated secondary switchgear:
SafeRing / Safeplus
Air-insulated secondary switchgear: UniSec
Air-instulated switch-disconnector: NALF
Recloser: Gridshield
Circuit-breaker: VD4
6 Transformers: Dry-type transformers,
oil-immersed transformers
7 MV line - transformer protection relay
8 General protection relay
9 GSM telephone actuator
10 Interface protection system:
ABB Relion® Family, REG615
11 Surge protection Device
12 Fuse disconnectors
13 Energy Meter - EQ Meters

The surge protection device installed in the AC side of the inverters shall be Class I SPDs.
SPDs are recommended also in the MV incoming line.
The AC LV line shall be protected using a moulded case circuit-breaker. The maximum output current ($I_{AC\ MAX}$) of each one of the inverters is 1925 A.
To protect the AC connection of each inverter, an overcurrent protection device with the following features shall be installed:

- Type: Automatic circuit-breaker;
- Voltage rating: = inverter V_{AC};
- Current rating: > inverter $I_{AC\ MAX}$; for the selected inverter $I_{AC\ MAX}$ = 1925 A; then the load protection breaker current rating = 2000 A;
- Magnetic protection characteristic: B/C

For power transform LV/MV dimensioning please, refer to the ABB Technical guide “The MV/LV transformer substations”.
For MV line dimensioning please, refer to the ABB Technical guide “Installation and operating principles for medium voltage switchgear”
For protection selecting please, refer to the ABB Technical guide “Protection criteria for medium voltage networks”.

B.2 PV plant with string inverters (2MW)

We wish to carry out the dimensioning of a PV production plant utility scale grid-connected; it shall be connected to the MV public utility network (20 kV / 50 Hz).
The PV plant will be installed on the roofs of a group of carports in the parking area of a shopping center in Spain near to Sevilla.

B.2.1 Inclination and orientation of the modules

Each carport is oriented as shown in Figure 96.

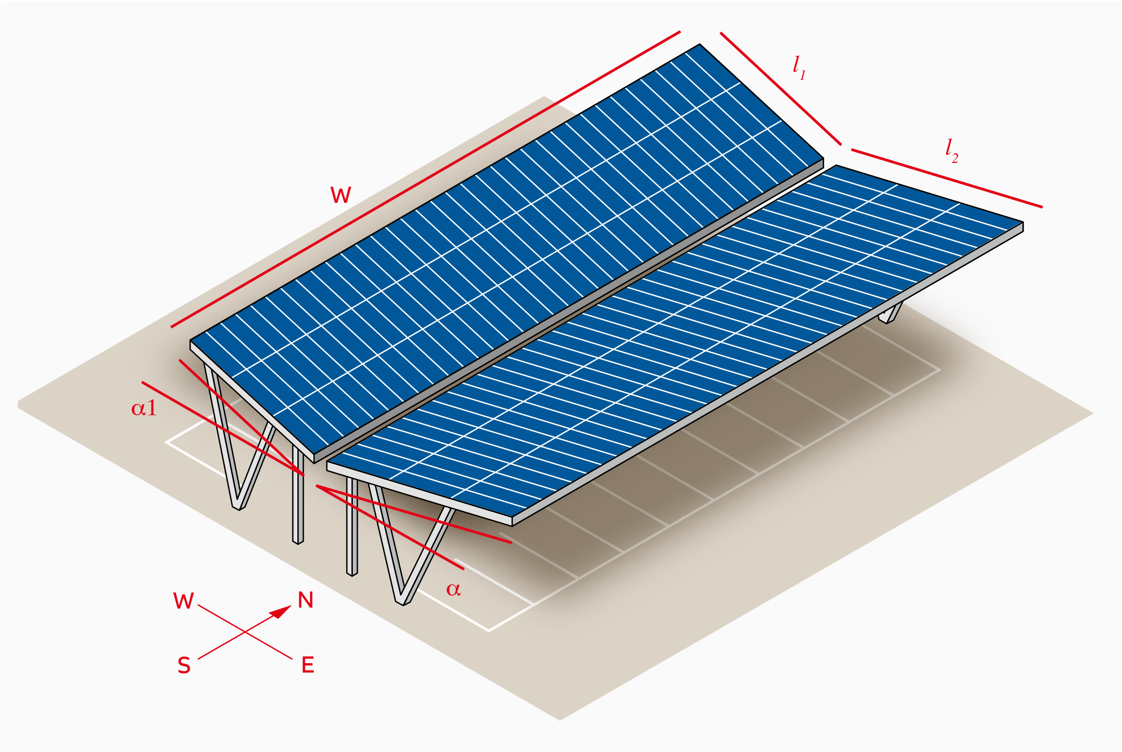


Figure 96
Carport with double pitch angle

B.2.2 Site reference temperature

The maximum and the lowest temperature that can be expected at the PV installation site are necessary for the strings design (according to IEC 60364-7-712). The temperatures of the solar cells depend on the selected mounting system and on the ambient temperature. For tilt angle ground mounted installation ΔT between ambient e cell temperature is +30 °C.
The maximum ambient temperature in the PV installation site near to Sevilla is estimated (according to weather databases) 31 °C; then the maximum cell temperature that shall be used for the string sizing in the ground mounted PV installation is 61 °C.
The minimum ambient temperature in the PV installation site near to Sevilla is estimated (according to weather databases) 2 °C; then the minimum cell temperature that shall be used for the string sizing in the ground mounted PV installation is 2 °C.

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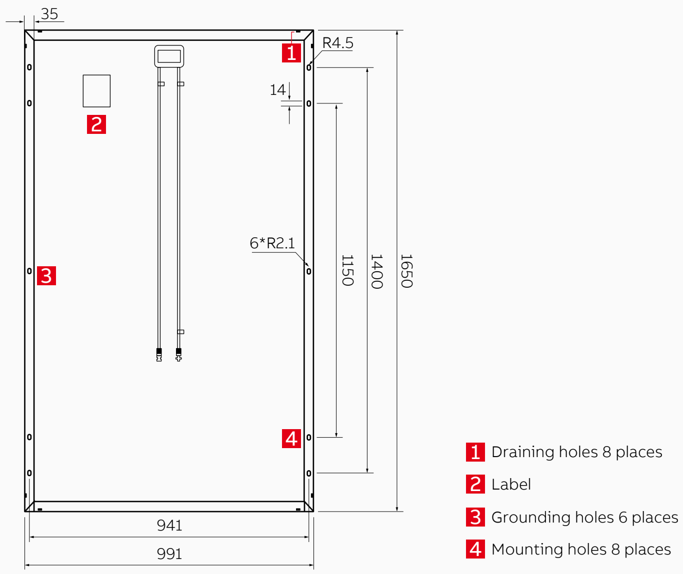
B.2.3 PV module type selection

In order to size the PV field according to the land availability, the PV module type shall be selected.

—
Figure 97
PV module data

PV MODULE DATA			
Manufacturer:	PV Module manufacturer B		
Model:	280W PV module – 60 polycrystalline cells		
Nominal Power [W]:	280	**Grounding:**	N/D
Open Circuit Voltage - Voc [V]:	38.65	**Short Circuit Current - Isc [A]:**	9.37
Max Power Voltage - Vmp [V]:	31.61	**Max Power Current - Imp [A]:**	8.86
Temperature coeff. Voc [V/°C]:	-0.128	**Temperature coeff. Isc [mA/°C]:**	5.43
Temperature coeff. Voc [%/°C]:	-0.331	**Temperature coeff. Isc [%/°C]:**	0.058
Max.Sys.Volt (IEC) [V]:	1500	**Temperature coeff. Pmax [%/°K]:**	-0.4

—
Figure 98
Dimensions of the selected module type



Determining the PV module max V_{OC} (according to IEC 60364-7-712)

The maximum open circuit voltage ($V_{oc\,MAX}$) of the selected PV module (60 polycrystalline 6” cells rated 280W at STC) is 38.65 V at STC.

The minimum ambient temperature in Sevilla (Spain) is 2 °C.

The voltage temperature coefficient (β) of the above PV module is -0.331 [%/K].

—
Equation 135

$$V_{OC\,MAX} = 38.65 \cdot \left[1 + (-0.331\%) \cdot \left((2) - 25\right)\right] = 38.65 \cdot [1 - 0.00331 \cdot (2 - 25)]$$
$$V_{OC\,MAX} = 38.65 \cdot [1 + 0.00331 \cdot 23] = 41.59\ V$$

Determining the PV module min V_{MPP}

The minimum MPP voltage ($V_{MPP\,min}$) of the selected PV module (60 polycrystalline 6” cells rated 280 W at STC) is 31.61 V at STC.

The maximum ambient temperature in Sevilla (Spain) is 31 °C and then the maximum cell temperature that shall be used for the string sizing in the ground mounted PV installation is 61°C.

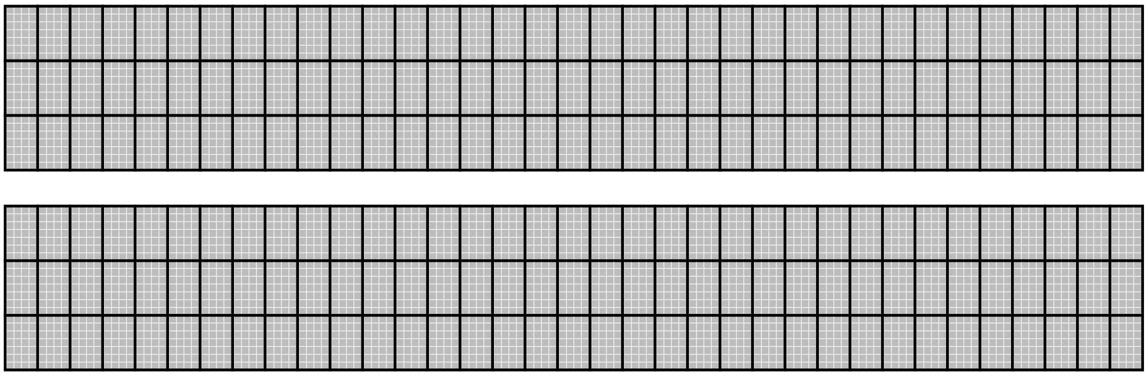
The voltage temperature coefficient (β) of the above PV module is -0.331 [%/K].

—
Equation 136

$$V_{MPP\,min} = 31.61 \cdot [1 + (-0.331\%) \cdot (61 - 25)] = 31.61 \cdot [1 - 0.00331 \cdot (36)]$$
$$V_{MPP\,min} = 31.61 \cdot [1 - 0.00331 \cdot 36] = 27.84\ V$$

B.2.4 Array physical configurations

According to length of west pitch and east pitch of each carport, 3 rows of selected modules could be installed in portrait condition.
According to width of west pitch and east pitch of each carport, 35 columns of selected modules could be installed in portrait condition.



—
Figure 99
single carport
modules positioning

The carports will be grouped in groups of 3.
The group of carports are positioned in the parking area according to the parking area internal roads.

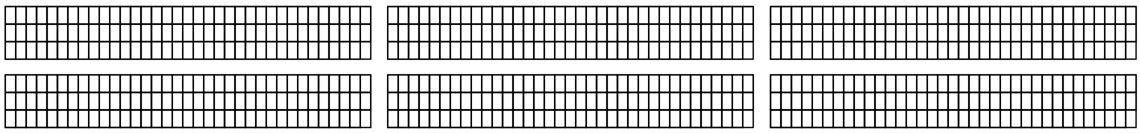


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Figure 100
group of carports
modules positioning

B.2.5 Inverter size selection

The selection of the inverter and of its sizing is carried out according to the PV generator rated power. The available carports are 36 (12 groups of 3 carports). According to the selected PV modules power rate, the PV generator rated power ($P_{DC\ PV\ GEN}$) is 2.1168 MW.
Considering the distribution of the carports and considering that each carport is structured with 2 pitch angles, the use of string inverters is recommendable.

—
Figure 101
Inverter data

INVERTER DATA			
INPUT		**OUTPUT**	
Nominal Input Power ($P_{DC,r}$) **[W]:**	177000	**Rated active power** ($P_{AC,r}$) **[W]:**	175000
Maximum power input ($P_{DC,\ max}$) **[W]:**	188000	**Maximum active power** ($P_{AC,max}$@cosφ=1) **[W]:**	185000
Maximum power MPPT ($P_{MPPT,max}$) **[W]:**	15600	**Maximum apparent power** (S_{max}) **[VA]:**	185000
Maximum input voltage (V IN $_{max\ (abs)}$) **[V]:**	1500	**Rated voltage** ($V_{AC,r}$) **[V]:**	800
Min input voltage for MPPT operation ($V_{in,min(mppt)}$) **[V]:**	70% Vstart	**Nominal frequency** (f_r) **[Hz]:**	50
Max input voltage for MPPT operation ($V_{in,max(mppt)}$) **[V]:**	1500	**Number of phases** (n_p)**:**	3
Start voltage (default) ($V_{start,def}$) **[V]:**	750	**Maximum current** ($I_{AC,max}$) **[A]:**	134
Start voltage (range) ($V_{start,range}$) **[V]:**	850-1350	**Rated Power Factor** (cosφ)**:**	1.00
Number MPPT (N_{MPPT})**:**	12	**Power Factor (range)** ($\cos\phi_{(range)}$)**:**	-0.10÷ 0.10
Maximum current MPPT ($I_{MPPT,max}$) **[A]:**	22		
Short circuit current MPPT (I SC $_{max}$) **[A]:**	30		

B.2.6 Determining the Maximum Number of PV Modules per String

According to the above module maximum open circuit voltage at the minimum ambient temperature in Sevilla ($V_{OC\ MAX}$= 41.59 V), the maximum number of PV modules connected in series that could be connected to the inverter is:

—
Equation 137

$$N_{MAX\ Module} \leq \frac{V_{MAX\ Inverter}}{V_{OC\ MAX\ Module}} = \frac{1500}{41.59} = 36.06$$

The maximum system voltage of all the components of the PV system (combiner boxes, switch, connectors, cables, PV Modules, etc.) shall be compatible with the maximum input voltage of the inverter (1500 V).
The maximum system voltage of the selected PV modules is 1500 V and then the modules are compatible with the maximum input voltage of the inverter.

B.2.7 Determining the Minimum Number of PV Modules per String

In case the string voltage falls below the minimum MPP voltage of the inverter (850 V), MPP tracking is not possible or yield losses can occur. The minimum number of PV modules connected in series to assure that the string voltage at MPP condition is always above the minimum MPP voltage of the inverter is:

—
Equation 138

$$N_{\min mod} \geq \frac{V_{\min MPPT\ Inverter}}{V_{MPP\ min\ Module}} = \frac{850}{27.84} = 30.53$$

B.2.8 Number of PV Modules per String

The selected PV inverter is equipped with 12 MPPT.
The number of PV modules per string must:

- not exceed the Maximum Number of PV Modules per String (36);
- not be less than Minimum Number of PV Modules per String (31).

Determining the Maximum PV Module Current

— Equation 139

$$I_{SC\ OPC\ MAX\ Module} = I_{SC\ STC} \cdot [1 - \alpha \cdot (25 - T_{cell})] = 9.37 \cdot [1 - 0.00058 \cdot (25 - 61)] = 9.56\ A$$

Determining the Maximum PV string Current

— Equation 140

$$I_{SC\ OPC\ MAX\ Module} = I_{SC\ OPC\ MAX\ string} = 9.56\ A$$

Determining the String Number
The maximum number of strings for each MPPT is:

— Equation 141

$$N_{MAX\ string} \leq \frac{I_{Max\ input}}{I_{SC\ OPC\ MAX\ string}} = \frac{22}{9.56} = 2.30$$

B.2.9 Definitive inverter layout

In order to optimize the cabling of the modules, is a best practice to consider the array physical configurations (panel configuration) in the selection of the string dimensions.

The best stringing option is:

- 2 strings of 35 PV (carport 1 east pitch) modules connected in MPPT1 (19.6 kW) of the inverter;
- 2 strings of 35 PV (carport 1 west pitch) modules connected in MPPT2 (19.6 kW) of the inverter;
- 2 strings of 35 PV (carport 2 east pitch) modules connected in MPPT3 (19.6 kW) of the inverter;
- 2 strings of 35 PV (carport 2 west pitch) modules connected in MPPT4 (19.6 kW) of the inverter;
- 2 strings of 35 PV (carport 1 east pitch & carport 2 east pitch) modules connected in MPPT5 (19.6 kW) of the inverter;
- 2 strings of 35 PV (carport 1 west pitch & carport 2 west pitch) modules connected in MPPT6 (19.6 kW) of the inverter;
- 2 strings of 35 PV (carport 3 east pitch) modules connected in MPPT7 (19.6 kW) of the inverter;
- 2 strings of 35 PV (carport 3 west pitch) modules connected in MPPT8 (19.6 kW) of the inverter;
- 1 strings of 35 PV (carport 3 east pitch) modules connected in MPPT9 (9.8 kW) of the inverter;
- 1 strings of 35 PV (carport 3 west pitch) modules connected in MPPT10 (9.8 kW) of the inverter.

According to this configuration, 1 inverter will be connected to 3 carports.
The PV arrays will be connected then to 12 inverters.
According to this configuration the total power of the PV field is 2.1168 MW."

B.2.10 DC Combiner boxes

The connection of modules in series is made on the modules themselves, while the parallel connection of the strings is made directly to the inverter; the string inverter itself usually contain:

- gPV fuses in order to protect the single string embeds;
- DC switch;
- SPD.

The DC combiner boxes are not required.

B.2.11 Choice of string cables

The installation is in Europe and then the cable shall respect the European coding for solar cables: the cables shall be H1Z2Z2-K.

Considering that:

- the maximum open circuit voltage ($V_{oc\,MAX}$) of the selected PV module (60 polycrystalline 6" cells rated 280 W at STC) is 38.65 V at STC;
- the maximum open circuit voltage ($V_{oc\,MAX}$) at lower temperature is 41.59 V;
- the strings are composed by 35 modules;

the maximum string open circuit voltage ($V_{oc\,MAX\,string}$) at lower temperature is 1455.65 V.

The cables voltage rating shall be chosen according to the maximum open circuit voltage ($V_{oc\,MAX\,string}$) and then > 1455.65 V.

The string cables shall be selected in order to maintain the voltage drop <2%.

Considering that:

- string cables will be disposed in perforated metal cable tray on the back side of the structures;
- in the same duct will put around 6 couple of string cables;
- the average length of the string circuit is 200 m;

the following solar cable is selected for the strings:

cable type: H1Z2Z2-K

cross section: 6 mm^2

Rated voltage DC: 1.5 kV

Ambient temperature in operation: -40 °C up to +90 °C

I_0 Current carrying capacity for single cable free in air: 55 A

Max. short-circuit temperature of the conductor: 250 °C (5 s.)

The continuous current-carrying capacity I_z shall be verified and it shall be:

—
Equation 142

$$I_z \geq I_{sc\;MAX\;string} = I_{SC\;STC\;string} \cdot 1.25$$

The Maximum PV string Current, for cable dimensioning, is $I_{SC\,MAX\,string}$ = 11.71 A.

According to this, the continuous current-carrying capacity I_z of the PV string cables, for wire sizing, shall be:

—
Equation 143

$$I_z \geq 11.71\;A$$

The current carrying capacity I_z of the solar cables disposed in perforated metal cable tray at the operating temperature of 70 °C results according to IEC 60364-5-52 is I_z= 36.53 A.

The carrying capacity is greater than 1.25 times the I_{sc} of the string; then cables dimensioning is correct[44] and it is not necessary to protect PV string cables against overloads.

—
44
Ref. to paragraph 6.1.1

B.2.12. Inverter AC output

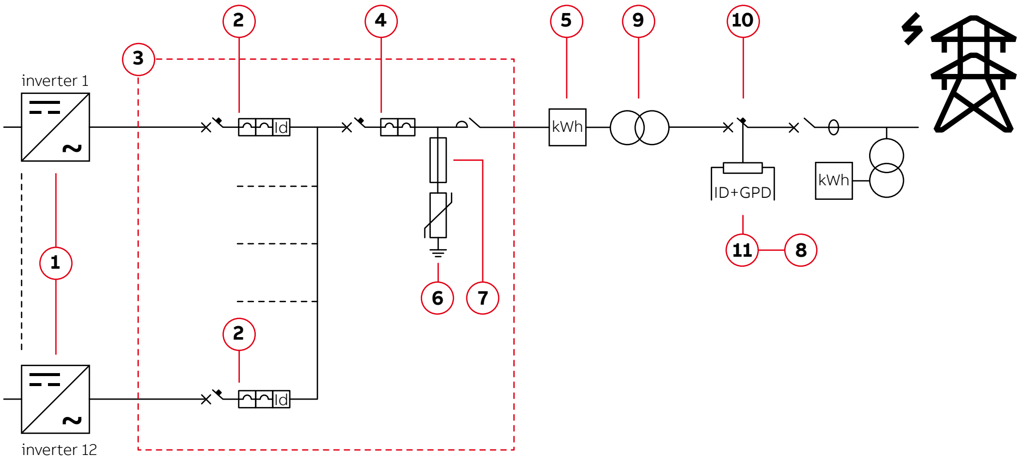
The string inverter itself contain:
- SPD;
- AC switch.

B.2.13. Choice of inverter AC cable

First of all, the maximum cable cross-section that could be connected to the inverter shall be verified in the inverter manual.
The cross-section of the AC line conductor cables must be sized in order to prevent unwanted disconnections of the inverter from the grid due to high impedance of the line that connects the inverter to the power supply; if the impedance is too high it causes an increase in the AC voltage which, on reaching the limit set by the standards in the country of installation, causes the inverter to switch off.
The cables must be sized:
- in order to maintain the voltage drop <2 %;
- according to IEC 60364-5-52.

B.2.14 AC combiner box

—
Figure 102
AC single line diagram



1 String inverter
2 Miniature circuit-breaker/Molded case circuit-breaker with residual current devices
3 AC combiner box
4 Air circuit-breaker
5 Energy meters: EQ meters and current transformers
6 Surge protective devices: OVR T1 / T1-T2 / T2 QS
7 Fuse disconnector: E 90
8 GSM telephone actuator: ATT

Medium-voltage products:
9 Transformers: Dry-type transformers, oil-immersed transformers
10 Gas-insulated secondary switchgear: SafeRing / Safeplus
Air-insulated secondary switchgear: UniSec
Air-insulated switch-disconnector: NALF
Recloser: Gridshield®
Circuit-breaker: VD4
11 Interface protection system: ABB Relion® Family

B.2.14.1 Circuit-breaker on the AC side of the inverter

To protect the AC connection line of each inverter, an overcurrent protection device with the following features shall be installed (these are the characteristic of a load protection switch referred to a single inverter installation):

- Type: Automatic circuit-breaker with differential thermal-magnetic protection;
- Voltage rating: = inverter V_{AC}; for the selected inverter V_{AC}= 800 V
- Current rating: > inverter $I_{AC\ MAX}$; for the selected inverter $I_{AC\ MAX}$ = 134 A; then the load protection breaker current rating = 150 A;
- Magnetic protection characteristic: characteristic B/C or adjustable magnetic protection threshold
- Number of poles: 3 or 4 depending from the system type.

The residual current protection device must meet the following characteristics:

- Type of differential protection[45]: A or AC;
- Differential sensitivity: for the selected inverter 1 A.

—
45
The inverter producer declares that the transformerless inverters, in terms of their construction, do not inject continuous ground fault currents and therefore there is no requirement that the differential protection installed downstream of the inverter be type B in accordance with IEC 60755 / A 2.

B.2.14.2 SPD

The surge protection device installed in the AC side of the inverters shall be Class I SPDs.

B.2.14.3 LV AC side main circuit-breaker

To protect the AC connection of all the inverter, an overcurrent protection device with the following features shall be installed:

- Type: Air circuit-breaker;
- Voltage rating: = inverter V_{AC}; for the selected inverter V_{AC}= 800 V
- Current rating: > inverter $I_{AC\ MAX}$; for the selected inverter $I_{AC\ MAX}$ = 134 A; 12 inverters are interconnected; then the load protection breaker current rating = 2000 A;
- Magnetic protection characteristic: adjustable magnetic protection threshold
- Number of poles: 3 or 4 depending from the system type.

B.2.15 MV line and protections

For power transform LV/MV dimensioning please, refer to the ABB Technical guide “The MV/LV transformer substations”.
For MV line dimensioning please, refer to the ABB Technical guide “Installation and operating principles for medium voltage switchgear”.
For protection selecting please, refer to the ABB Technical guide “Protection criteria for medium voltage networks”.

Annex C - Maintenance

Annex C - Maintenance

Introduction

Every PV array is an electric energy production plant and then an electric installation. As with any electrical system, the operation and maintenance (O&M) of photovoltaic systems is necessary and mandatory.

Usually multiple stakeholders, with different roles and responsibilities, interact in the O&M phase:

- Asset Owner: the asset owner is the investor that contributes to financing of construction and operation of the PV powerplant.
- Asset Manager: the asset management ensure the optimal profitability of the PV power plant and supervise the O&M activities and the energy production. The asset manager aim is also to manage, from financial and technical point of view, the fulfilment of all administrative, fiscal, insurance and financial obligations of the SPVs.
- Technical Advisor: technical advisor is an expert engineer that provide specialised services to safeguard the PV plant energy production (e.g. diagnostic analysis, state of the PV plant verification, etc.)
- O&M contractor: the O&M contractor is in charge of the activities and operations on the PV plant (e.g. electric activities, spare parts management, periodical verification, etc.). Because of the shock and flash hazards present in PV systems, it is essential that O&M provider personnel interacting with the system have appropriate training, use appropriate personal protective equipment, and follow safe procedures.

The maintenance activities could be categorized as follow:

- Preventive Maintenance: Elettropedia[46] defines predictive maintenance in the IEV ref 192-06-05 as follow: “maintenance carried out to mitigate degradation and reduce the probability of failure”.
  It is the core service of the PV plant maintenance comprises regular scheduled[47] visual and physical inspections of all key components according to the recommendations issued by the Original Equipment Manufacturers (OEMs) and to the PV plant O&M manual. All these activities are included in a detailed annual Maintenance Plan: it provides an established time schedule with a specific number of iterations for carrying out the preventive maintenance.
- Corrective Maintenance: Elettropedia defines corrective maintenance in the IEV ref 192-06-06 as follow: “maintenance carried out after fault detection to effect restoration”.
  Corrective Maintenance generally includes three activities phases:
  1. Troubleshooting or Fault Diagnosis in order to identify and localise the fault cause;
  2. Temporary Repair in order to restore the required function of a faulty item for a limited time waiting for the definitive repair caring out;
  3. Repair in order to definitely restore the required function of a faulty item.

The corrective maintenance is generally extraordinary maintenance because it is necessary following to a major unpredictable event take place in the PV plant; generally, it is not included in the O&M Contract.

- Predictive Maintenance: the predictive maintenance is a condition-based maintenance carried out following a forecast derived from the analysis and evaluation of the significant parameters of the degradation of the item (according to EN 13306) or derived from the experiences. The predictive maintenance reduces emergency and non-planned work related to the fault of an item, increases the availability of the PV plant and reduces time to repair and optimise maintenance and Spare Parts Management costs.

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46
Electropedia (also known as the "IEV Online") contains all the terms and definitions in the International Electrotechnical Vocabulary or IEV which is published also as a set of publications in the IEC 60050 series that can be ordered separately from the IEC webstore
—
47
IEV ref 192-06-12 scheduled maintenance or planned maintenance is the maintenance carried out in accordance with a specified time schedule

C.1 Maintenance protocols

A lot of documents about best practices for maintenance of PV system are available in literature (e.g.: Solar Power Europe - Operation & Maintenance Best Practices Guidelines; NREL - Best Practices in Photovoltaic System Operations and Maintenance; etc.), by the way IEC is developing a new standard about the Maintenance of PV systems: IEC 62446-2 - Photovoltaic (PV) systems – Requirements for testing, documentation and maintenance – Part 2: Grid connected systems – Maintenance of PV systems.
This standard will include the maintenance protocols but it does not specify verification or maintenance intervals because they must be established by the O&M provider according to the site conditions.
Example of tasks and items subject to preventive maintenance are indicated in the Table 13.

Table 13

Component	Task
PV modules	Inspection for: - Cracks - Micro cracks - Breakage - Burn marks - Snail trails - Soil status or droppongs
	IR imaging of: - Junction boxes - Cells - PV modules internal connections - connectors
	Connectors check
Array	Animal or pest activity under array
	Periodic insulation resistance testing
	Check of not considered shadows
	Vegetation management - cutting, removing, control
Inverter	Verification of warning of signal
	Inverter internal checks
	Periodic maintenance – manufacturer specified
	Check of fans
	Cleaning of air filters
	Test of emergency stops and interlocks
Combiner boxes	Check torque marks on field terminations and re-torque field or factory terminals as needed
	Look for - debris - signs of water - Burn/arc discoloration on terminals, boards, fuse holders - Dust deposits on contact surfaces
	IR imaging of connections
	Fuse replacement (in case of triggering)
	Verification of SPDs
	Verification of Switch disconnector operation
Wiring	Verification of module/string wiring
	Performing of Periodic insulation resistance testing
Earthing	Earth system continuity test performing
Mounting System	Verification of Support structure rust, corrosion, sagging, deformation, breakage, bolt tightness
Tracker	Orientation verification
	Periodic maintenance according to manufacturer specifications
	Verification of safety sensors
Weather/Data Components	Sensor alignment, cleanliness, airflow
	Periodic calibration performing

C.2 Failures research

To maintain the PV system, the O&M provider shall have the PV installation documentation (e.g.: Wiring diagram, String layout, Datasheets, etc.) at disposal according to the IEC 62446-1 - Grid connected PV systems -Part 1: Requirements for system documentation, commissioning tests and inspection.
In order to search failure on PV field, some diagnostic test could be performed.
The main test that could be performed in the PV field are described in EC 62446-1:
- Continuity of protective earthing and equipotential bonding conductors;
- String open circuit voltage test;
- PV string current measurement;
- PV string short-circuit test;
- PV string combiner box test;
- Insulation resistance of the DC circuits;
- String I-V curve test;
- Blocking diode test;
- IR inspection.

More details about the IR inspection of PV modules are available on IEC TS 62446-3 - Photovoltaic (PV) systems - Requirements for testing, documentation and maintenance - Part 3: Photovoltaic modules and plants - Outdoor infrared thermography.

C.3 Revamping and repowering

Revamping and repowering are usually considered to be part of extraordinary maintenance.
Revamping consists in replacing the malfunctioning components with new ones that are more efficient (keeping the power of the plant fixed) and/or installing items that could optimize the PV installation performance and/or re-engineering the PV installation.
Repowering intervention consists in replacing components with new ones that are more efficient with the aim to obtain; greater power from the plant while maintaining its contour characteristics unaltered (e.g. the field occupation).
There are several reasons why revamping / repowering of PV plants can be necessary:
- Aging PV-Assets;
- Unavailability of spare parts and support for key items (e.g. PV modules, inverters, etc.);
- Technological Improvements;
- Price of key component decreasing;
- Substantially: the CAPEX related to installing new components is less than OPEX related to maintain old components.

Example of revamping activities are:
- PV modules replacement;
- Inverter replacement;
- MV/LV transformer replacement;
- Power optimizer installation;
- Removing of LV/LV transformer (when it is allowed by regulations);
- String re-cabling in order to reduce the effects of unexpected shadows;
- Changing of tilt angle of the fixing structure in order to reduce the effect of shadows.

C.4 Monitoring & supervision system

In general, the monitoring system of a PV plant should allow to monitor the operation parameters of the components involved in the energy conversion. The monitoring system is necessary to monitor the energy performance of the PV system and identify troubles and failures.
The required accuracy and complexity of the monitoring system depends on the PV system size and user objectives. The monitoring system, according to IEC 61724-1, could be classified as follow:
- Class A – High accuracy;
- Class B – medium accuracy;
- Class C – basic accuracy.

C.4.1 Standards

The reference standards related to the monitoring system are:
- IEC 61724-1 - Photovoltaic system performance - Part 1: Monitoring
- IEC 61724-2 - Photovoltaic system performance - Part 2: Capacity evaluation method
- IEC 61724-3 - Photovoltaic system performance - Part 3: Energy evaluation method

C.4.2 Monitoring system component and sensor

IEC 61724-1 defines the required sensor for the monitoring system and their number depending from the monitoring system class.
The parameters that could be measured and acquired are:
- In plane irradiance (POA);
- Global Horizontal Irradiance (GHI);
- PV module temperature;
- Ambient temperature;
- Wind speed;
- Wind direction;
- Rain fall;
- Array voltage;
- Array current;
- Array power;
- AC output voltage;
- AC output current;
- AC output power;
- AC output energy.

All the data are collected on site by dataloggers. The sampling and recording interval are defined by IEC 61724-1 according to the monitoring system class.

10

C.4.3 Key Performance Indicators (KPIs)

The main KPIs used for the PV system monitoring are indicated here below.
Reference yield: it represents the energy obtainable under ideal conditions, with no losses, over a certain time period.

—
Equation 144

$$Y_{r\,(i)} = \frac{H_{(i)}}{G_{STC}}$$

Where:
$Y_{r\,(i)}$ reference yield for the time period i expressed in peak sun hours (h) or (kWh/kW);
$H_{(i)}$ is the measured irradiation on modules' plane for the time period i (kWh/m^2);
G_{STC} the reference irradiance at standard test conditions (STC - 1000 W/m^2).

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Final system yield - Specific yield: it is the measure of the total energy generated per kWp installed over a certain period of time.

—
Equation 145

$$Y_f = \frac{E_{out}}{P_0}$$

Where:
Y_f Plant Specific yield for the time period i, expressed in (kWh/kWp) or peak sun hours (h);
E_{out} Plant energy production or Plant energy metered for the time period i (kWh);
P_0 Plant Peak DC power (nominal power) (kWp).

Performance Ratio (PR): it is a quality indicator of the PV plant.

—
Equation 146

$$\mathrm{PR} = \frac{Y_f}{Y_r}$$

Other KPIs are defined by IEC 61724 series.

C.5 Maintenance of inverters

C.5.1 String inverter

In the maintenance of the string inverters a distinction shall be done according to the type of ventilation (cooling): it could be natural convection or forced ventilation.
In case of natural convection, the dissipation is entrusted to the natural flow of air through the fins of the heat sink. This kind of inverter can be considered as "maintenance free" with the exception of the cleaning of the heat sink to ensure the correct air flow.

In case of forced ventilation, the fans "push" fresh air onto the fins of the heat sink: the forced ventilation is more effective than the natural convection and requires less temperature exchange surface (lower heat sinks and therefore less cumbersome); however, forced ventilation requires the presence of fans that are components subject to wear in the long term (replacement is generally required after 10 years of operation). Moreover periodic cleaning of the air intake filter / grille is required. The frequency very often depends on the characteristics of the place of installation (presence of dust, salt, dirt, etc.).
In any case, the customer shall refer to the indications that are given in the product manual, both in terms of periodic maintenance and in terms of lifecycle or prior replacement of components subject to wear.

C.5.2 Centralized inverter

Centralized inverters generally require maintenance. The maintenance plan usually includes:
- Cleaning the air intake filters;
- Thermographic (IR imaging) verification of connections.

In general, maintenance (in addition to the intervention itself and therefore the benefits it brings) is an operation that allows to check the status of the machine and eventually evaluate targeted updating activities

Abbreviations and acronyms

AC	Alternating Current
ACB	Air Circuit-Breaker
AM	Air Mass
a-Si	amorphous Silicon
BAPV	Building Applied PV
BIPV	Building Integrated PV
BOS	Balance Of System
CAPEX	CAPital Expenditure
CdTe	Cadmium Telluride
CIGS	Copper Indium Gallium Selenide
CIS	Copper Indium Selenide
CPV	Concentrator Photovoltaics
c-Si	crystalline Silicon
CT	Current Transformer
CZTS	Copper Zinc Tin Sulfide
DC	Direct Current
DSC	Dye-sensitized Solar Cell
DSO	Distribution System Operator
DSSC	Dye Sensitized Solar Cells
EWT	Emitter Wrap Through
FF	Fill Factor
GaAs	Gallium Arsenide
GD	General Device
GDT	Gas Discharge Tubes
GenD	Generator Device
GHI	Global Horizontal Irradiation
GSM	Global System for Mobile Communications
GTI	Global Tilted Irradiation
HJT	Heterojunction
HV	High Voltage
IBC	Interdigitated Back Contact solar cells
ID	Interface Device
IGBT	Insulated Gate Bipolar Transistor
IPS	Interface Protection System
IT	Instrument transformer
ITO	Indium Tin Oxide
LETID	light and Elevated Temperature Induced Degradation
LID	Light Induced Degradation
LPL	Lightning Protection Level
LPS	Lightning Protection System
LV	Low Voltage
MCB	Miniature Circuit-Breaker
MCCB	Molded Case Circuit-Breaker
MJ	Multi-Junction
MOV	Metal Oxide Varistors
MPP	Maximum Power Point
MPPT	Maximum Power Point Tracker
MV	Medium Voltage
MWT	Metalization Wrap Through
OPC	Operative Conditions
OPV	Organic Photovoltaics
OSC	Organic Solar Cells
PID	Potential-Induced Degradation
PR	Performance Ratio
PSC	Perovskite Solar Cells
PV	Photovoltaic
PWM	Pulse Width Modulation
QDSC	Quantum Dot Solar Cell
RCD	Residual Current Device
SCC	Short Circuit Capacity
SPD	Surge Protection Device
STC	Standard Test Conditions
VT	Voltage Transformer

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https://new.abb.com/low-voltage/industries/solar

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