Sustainable Integration of Renewable Energy Sources (Solar PV) with SEC Distribution Network Low Voltage and Medium Voltage

Best Practice for the Design of a small-scale solar PV system

Version 2

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1 SCOPE

Designing of Solar PV Systems needs competence and knowledge in several fields that include the solar radiation, the solar energy conversion into electricity, the behaviour of the solar devices and equipment.
Furthermore, a technical background on electric plants, use of components and safety measures is necessary in order to obtain efficient and safe installations.
Although these Guidelines consider only Small-Scale PV Systems that are connected to the distribution network, and therefore isolated systems are not taken into account, the types of Solar PV Systems that can be adopted are numerous and it is possible to choose among different solutions according to the:

- PV technology, that is mono or multi-crystalline silicon, Thin-film, etc. ,
- System architecture, in terms of DC configuration, strings, arrays, multi-arrays, AC modules, etc. ,
- PV modules deployment and supporting structures, that is ground (or floor) placed structures, elevated structures, building-integrated installations, etc. .

There are also further aspects to be accounted for as concerns the cable routing, the inverter placement, the type of protection devices, only to mention a few.
This report has not the ambition to cover all the possibilities, but it is aimed to focus upon the most important topics that are important to face when designing a Solar PV System. However, a suggestion to refer to every subject more in detail by means of dedicated books and magazines is also given in the current document.
As regards the maintenance of Small-Scale PV Systems, it is observed that they are generally considered to be a very low maintenance means of power generation. However, Solar PV Systems do require some level of preventative and corrective maintenance to perform over a lifetime that can exceed 20 years. It is also noticeable that the level of maintenance required or recommended for a correct performance can vary considerably based on the Customer’s preference or contractual obligations for power production.

1.1 Notice to users

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Users should be aware that this document may be superseded at any time by the issuance of new editions or may be amended from time to time through the issuance of amendments, corrigenda, or errata. These Guidelines at any point in time consist of the current edition of the document together with any amendments, corrigenda, or errata then in effect. All users should ensure that they have the latest edition of this document, uploaded on SEC website.
Finally, the user shall refer to Saudi Building Code – Section 401 - Chapter 712, as well as to applicable SASO Standards or International Standards mentioned in these SEC documents, unless differently indicated in other SEC documents related to Small-Scale Solar PV Systems Regulations.

2 REFERENCE DOCUMENTS

[1] Technical Standards for the Connection of Small-Scale Solar PV Systems to the LV and MV Distribution Networks of SEC
[2] Guidelines that inform customers and installers in order to connect a solar PV system to distribution networks
[3] Inspection and Testing Guidelines
[4] PV on buildings and safety
[5] Safety related to the installation of rooftop solar PV systems
[6] The Saudi Building Code Electrical Requirements (SBC401) – 2007
[7] Small-Scale Solar PV Systems Regulations - Electricity & Cogeneration Regulatory Authority (ECRA) – ERD-TA-012 (V02/19)
[8] IEC 60364-6 – Low voltage electrical installations. Part 6: Verifications
[9] IEC 60364-5-52-Low-voltage electrical installations - Part 5-52: Selection and erection of electrical equipment - Wiring systems
[10] IEC 60364-7-712-Low voltage electrical installations - Part 7-712: Requirements for special installations or locations - Solar photovoltaic (PV) power supply systems
[11] IEC 61010 – Safety requirements for electrical equipment for measurement, control and laboratory use
[12] SASO IEC 61557 – Electrical safety in low voltage distribution systems up to 1000 V AC and 1500 V DC
[13] SASO IEC 61724-1 – Photovoltaic system performance. Part 1: Monitoring
[14] SASO IEC 61724-2 – Photovoltaic system performance. Part 2: Capacity evaluation method
[15] SASO IEC 61724-3 – Photovoltaic system performance. Part 3: Energy evaluation method
[16] SASO IEC 61730-2 – Photovoltaic (PV module safety qualification. Part 2: Requirements for testing
[17] SASO IEC 62446-1 – Photovoltaic (PV) systems. Requirements for testing, documentation and maintenance. Part 1: Grid connection systems. Documentation, commissioning, tests and inspection
[18] SASO IEC 62548 – Photovoltaic (PV) arrays. Design requirements
[19] NREL – Best Practices in PV System Operations and Maintenance (2015)
[20] Solar Power Europe – O&M Best Practices Guidelines (2016)
[21] Solar ABC – PV System Operations and Maintenance Fundamentals (2013)
[22] IEC 60909-0 - Short-circuit currents in three-phase AC systems - Part 0: Calculation of currents

3 COMPANION DOCUMENTS

The documents listed hereinafter have to be considered a compendium of the current document. Therefore, they should be carefully read in addition to this.

a) Technical Standards for the Connection of Small-Scale Solar PV Systems to the LV and MV Distribution Networks of SEC
b) Guidelines for Consumers, Consultants and Contractors to connect a Small-Scale Solar PV System to SEC distribution network
c) Inspection and Testing Guidelines

d) Inspection and Testing Checklist
e) Safety related to the installation of the Solar PV systems
f) PV on buildings and safety
g) Manual for the Maintenance of the Solar PV Systems

4 TERMS AND DEFINITIONS

AC module – PV module with an integrated inverter in which the electrical terminals are AC only

Active power (P) – Under periodic conditions, mean value, taken over one period, of the instantaneous product of current and voltage expressed in W. Under sinusoidal conditions, the active power is the real part of the complex power.

Apparent power (S) – Product of the r.m.s. voltage between the terminals of a two-terminal element or two-terminal circuit and the r.m.s. electric current in the element or circuit expressed in VA. Under sinusoidal conditions, the apparent power is the modulus of the complex power.

Building-Attached Photovoltaic Modules (BAPV modules) – Photovoltaic modules are considered to be building-attached, if the PV modules are mounted on a building envelope and the integrity of the building functionality is independent of the existence of a building-attached photovoltaic module.

Building Attached Photovoltaic system (BAPV system) – Photovoltaic systems are considered to be building attached, if the PV modules they utilize do not fulfil the criteria for BIPV modules

Building-Integrated Photovoltaic modules (BIPV modules) – Photovoltaic modules are considered to be building-integrated, if the PV modules form a construction product providing a function. Thus, the BIPV module is a prerequisite for the integrity of the building's functionality. If the integrated PV module is dismounted (in the case of structurally bonded modules, dismounting includes the adjacent construction product), the PV module would have to be replaced by an appropriate construction product.

The building's functions in the context of BIPV are one or more of the following:

- 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

Inherent electro-technical properties of PV such as antenna function, power generation and electromagnetic shielding etc. alone do not qualify PV modules as to be building-integrated.

Building-Integrated Photovoltaic system (BIPV system) – Photovoltaic systems are considered to be building-integrated, if the PV modules they utilize fulfil the criteria for BIPV modules

Cable type – Description of a cable to enable its rating and suitability for a particular use or environment to be determined (Note: In many countries this is done via a code number e.g. "H07RNF")

Data sheet – Basic product description and specification (Note: Typically one or two pages, not a full product manual)

Eligible Consumer – A person who has an Exit Point that meets the requirements of these Regulations and the Connection Conditions between the Distribution System and the Consumer's Premises as defined in the Distribution Code.

Exit Point– The joint point of delivery of electricity supply by SEC & export of surplus generation by Eligible Consumer linked to one single meter in a Premises.

Global horizontal irradiance (GHI) – Direct plus diffuse irradiance incident on a horizontal surface expressed in W/m^2

$I_{MOD\_MAX\_OCPR}$ – PV module maximum overcurrent protection rating determined by SASO IEC 61730-2 (Note: This is often specified by module manufacturers as the maximum series fuse rating).

In – The nominal rating of an overcurrent protection device

Inspection – Examination of an electrical installation using all the senses in order to ascertain correct selection and proper erection of electrical equipment

In-plane irradiance (Gi or POA) – The sum of direct, diffuse, and ground-reflected irradiance incident upon an inclined surface parallel to the plane of the modules in the PV array, also known as plane-of-array (POA) irradiance. It is expressed in W/m^2

Interface Protection (IP) - The electrical protection required to ensure that either the generating plant and/or any generating unit is disconnected for any event that could impair the integrity or degrade the safety and reliability of the distribution network.

Inverter – Electric energy converter that changes direct electric current to single-phase or polyphase alternating current

Irradiance (G) – Incident flux of radiant power per unit area expressed in W/m^2

Irradiation (H) – Irradiance integrated over a specified time interval expressed in kWh/m^2

$I_{SC\ ARRAY}$ – The short circuit current of the PV array at Standard Test Conditions (STC), and is equal to:

$I_{SC\ ARRAY} = I_{SC\ MOD} \times N_S$

where N_S is the total number of parallel-connected PV strings in the PV array

$I_{SC\ MOD}$ – The short circuit current of a PV module or PV string at Standard Test Conditions (STC), as specified by the manufacturer in the product specification plate (as PV strings are a group of PV modules connected in series, the short circuit current of a string is equal to $I_{SC\ MOD}$)

$I_{SC\ S\text{-}ARRAY}$ – The short circuit current of a PV sub-array at Standard Test Conditions (STC), and equal to:

$I_{SC\ S\text{-}ARRAY} = I_{SC\ MOD} \times N_{SA}$

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

Loss Of Mains (LOM) – Represents an operating condition in which a distribution network, or part of it, is on purpose or in case of fault separated from the main power system with the final scope of de-energization. This denotes also the protection which detects this condition and it is also known as anti-islanding.

Micro-inverter – Small inverter designed to be connected directly to one or two PV modules (Note: A micro inverter will normally connect directly to the factory fitted module leads and be fixed to the module frame or mounted immediately adjacent to the module)

Module integrated electronics – Any electronic device fitted to a PV module intended to provide control, monitoring or power conversion functions (Note: Module integrated electronics may be factory fitted or assembled on site)

NMOT – Nominal Module Operating Temperature, as defined by SASO IEC 61215-2, i.e. the equilibrium mean solar cell junction temperature within an open-rack mounted module operating near peak power in the following standard reference environment:

Tilt angle: (37 ± 5)°

Total irradiance: 800 W/m^2

Ambient temperature: 20 °C

Wind speed: 1 m/s

Electrical load: A resistive load sized such that the module will operate near its maximum power point at STC or an electronic maximum power point tracker (MPPT).

N_S – total number of parallel connected strings in a PV array

N_{SA} – total number of parallel connected strings in a PV sub-array

Power factor) – Under periodic conditions, ratio of the absolute value of the active power P to the apparent power S

PV array – Assembly of electrically interconnected PV modules, PV strings or PV sub-arrays.

PV cell – The most elementary device that exhibits the photovoltaic effect, i.e. the direct non-thermal conversion of radiant energy into electrical energy

PV module – PV modules consists of electrically connected PV cells and packaged to protect it from the environment and the users from electrical shock.

PV string – PV string consists of two or more series-connected PV modules

PV string combiner box – Junction box where PV strings are connected which may also contain overcurrent protection devices, electronics and/or switch-disconnectors

PV sub-array – A subset of a PV array formed by parallel-connected PV strings.

Protective earthing – Earthing of a point in equipment or in a system for safety reasons.

Residual current device (RCD) – is a sensitive safety device that switches off when the residual current exceeds the operating value of the device

Residual current monitor (RCM) – device or association of devices which monitors the residual current in an electrical installation, and which indicates a fault when the residual current exceeds the operating value of the device or when a defined step change is detected

Small-Scale Solar PV System – As per ECRA Regulations, a solar PV installation of not more than 2MW and not less than 1kW capacity that is installed in one Premises and connected in parallel to the Distribution Network.

Standard test conditions (STC) – reference values of in-plane irradiance (1000 W/m^2), PV cell junction temperature (25 °C), and the reference spectral irradiance defined in SASO IEC 60904-3

Switch – Mechanical device capable of making, carrying and breaking currents in normal circuit conditions and, when specified, in given operating overload conditions. In addition, it is able to carry, for a specified time, currents under specified abnormal circuit conditions, such as short-circuit conditions.

Testing – implementation of measures in an electrical installation by means of which its effectiveness is proved (Note: It includes ascertaining values by means of appropriate measuring instruments, said values not being detectable by inspection)

Verification – all measures by means of which compliance of the electrical installation to the relevant standards is checked

5 GLOSSARY

In addition to those in 4 which need a definition, the following acronyms and symbols are used throughout the document:

cos φ	Power factor
ECRA	Electricity and Co-Generation Regulatory Authority
kWp, Wp	kW peak, W peak (units usually adopted to refer to the size of PV modules)
LOM	Loss Of Mains
LV	Low Voltage (namely 220/127 V or 380/220 V or 400/230 V)
MPPT	Maximum Power Point Tracking
MV	Medium Voltage (namely 13.8kV or 33 kV)
P	Active power
Pnom	Nominal active power of equipment
p.u. (or pu)	per unit
PV	(Solar) PhotoVoltaic
Q	Reactive Power
RCD	Residual Current Device
RCCB	Residual Current Circuit Breaker
SEC	Saudi Electricity Company
STC	Standard Test Conditions
V	Voltage
Vnom	Nominal Voltage

6 SOLAR RESOURCE AND TECHNOLOGY

6.1 The sun as an energy source

Every day we receive from the Sun thousands times the energy we consume but the solar energy is distributed on the Earth's surface, and thus large collection surfaces are required to exploit it.

Furthermore, if considering a given area, the sun energy is discontinuous, mainly for the following reasons:

- Variability during the day from sunrise to sunset and complete absence in the night periods
- Seasonal variations
- Meteorological conditions (clouds, fog, sandstorms, etc.)

The daily variability is due to the Earth rotation, which is the spinning of the Earth around its axis. One rotation takes 24 hours and is called a solar day.

The seasonal variation is due to the orbit of the Earth around the sun, and this rotation is called Earth revolution and takes 365 1/4 days to complete one cycle. The Earth's orbit around the sun is elliptical, thus the Earth's distance from the Sun varies at different times of the year.

Outside the Earth atmosphere, the solar irradiation has an average value of 1367 W/m^2 ±3%, called Solar constant. The variation of ±3% is due to the seasonal variation of the Earth's distance from the Sun.

From Figure 1, we can understand the effect of the Earth atmosphere on incoming solar irradiation as follow:

- A portion of the solar energy arrives directly to the ground (Direct or Beam radiation)
- A portion is diffused due to cloud and water molecules present in atmosphere (Diffused radiation)
- The remaining portion is lost by reflection and absorption by various constituents of atmosphere.

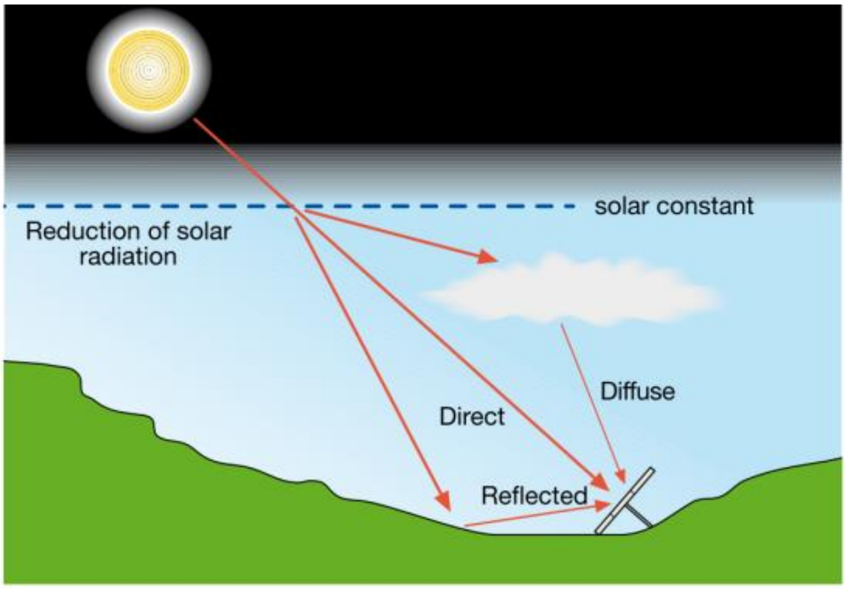


Figure 1 – Effect of the atmosphere on the sunlight

As a consequence, the trend of the solar radiation received at the ground is partially unpredictable because it depends on the local weather conditions. However, if we consider historical data collected by meteorological stations it is possible to have time-averaged data on an hourly interval for daily or monthly or yearly basis. Figure 2 Shows average annual solar radiation received in KSA referred from SolarGIS database a third party meteo data service provider.

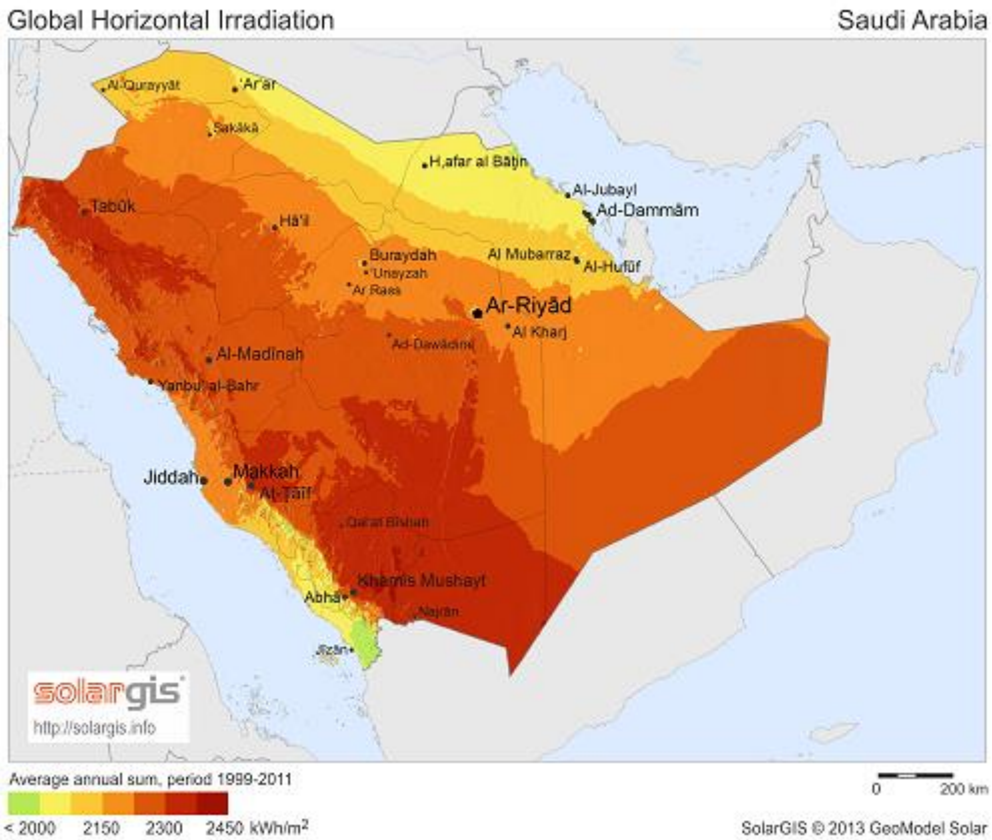


Figure 2 – Example of a yearly solar map for the Saudi Arabia

There are several databases on solar radiation and climate data that cover all the world or specific regions. In the Kingdom of Saudi Arabia it is possible to refer to the monitoring network developed by the King Abdullah City for Atomic and Renewable Energy (K.A.CARE).

The solar databases contain the global horizontal, Direct solar radiation and the Diffuse solar radiation on a horizontal surface expressed in kWh/m^2day. These data are normally available on hourly interval for daily or on a monthly basis and on a yearly basis or as a long-term average.

The passage from the horizontal plane to a tilted and differently oriented plane, representative of a PV system as shown in Figure 3, needs calculations that are normally made by using specific software. In the figure it can be seen that there is also a Reflected component of the solar radiation that can be considered negligible for moderate values of tilt angle.

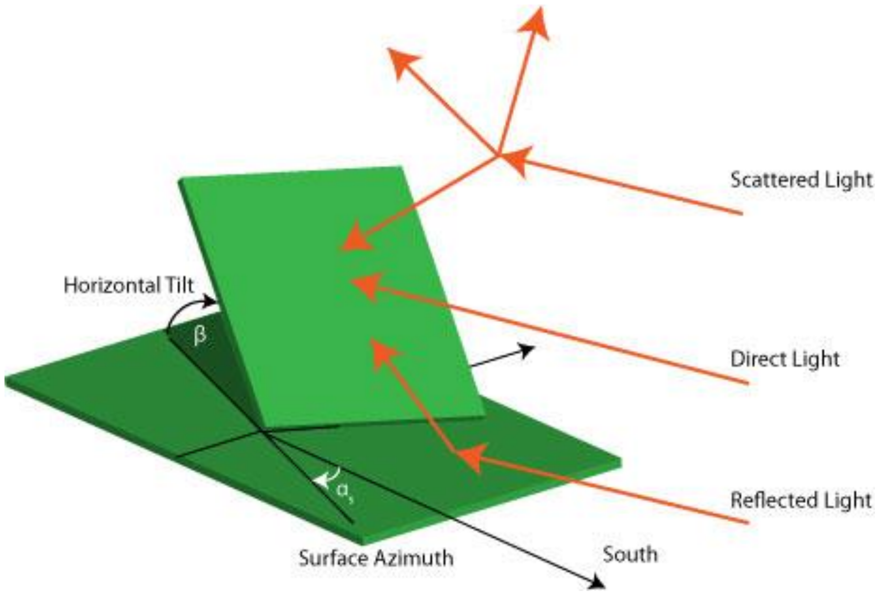


Figure 3 – Representation of Direct, Diffuse and Reflected solar radiation on a tilted and oriented surface

Further than the amount of the solar energy lost, the effects of the atmosphere is also related to the spectral composition of the solar radiation. Figure 4 shows the variation of the spectrum at different wavelengths before and after the crossing of the atmosphere.
The curve refers to the condition AM 1.5, namely the 1.5 times crossing of the average thickness of the atmosphere, corresponding to an incident angle of about 45° from the zenith (vertical axis).

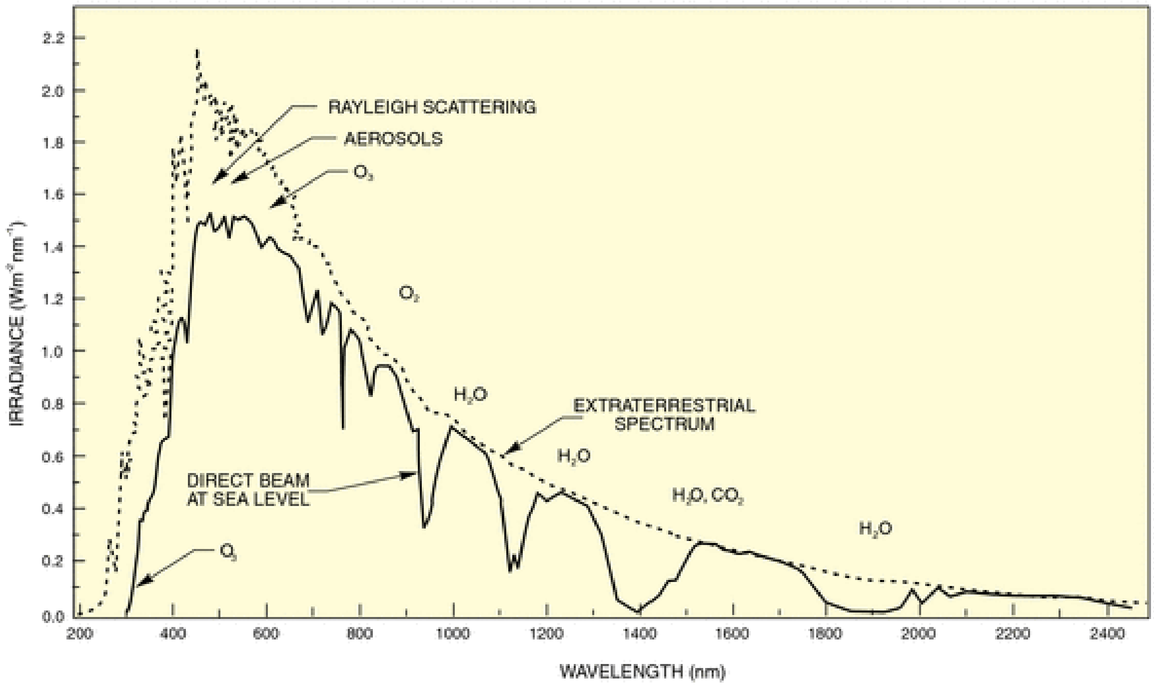


Figure 4 – Spectrum of the solar radiation out of the earth atmosphere compared to the spectrum at sea level and the influence of the atmospheric gaseous components

The distribution of the spectrum of the solar radiation has a fundamental importance in the photovoltaic conversion of the sunlight, because the PV cells, depending on their material, are able to convert only a portion of the spectrum into electricity.

6.2 PV Technology

6.2.1 PV cells

Solar systems are based on devices that transform sunlight into electricity, the PV cells, which perform the photovoltaic conversion. PV cells are composed of semiconductors purposely designed to be exposed to the sun light and collect as much energy as possible. Not surprisingly their shape has a thin thickness but a wide front surface.

The most widely used PV cells are made with crystalline silicon (mono or poly-crystalline as shown in Figure 5), whose shape is normally square or pseudo square (with edges trimmed) and whose thickness usually is no more than 0.2 mm. Crystalline PV cells can be obtained by a single crystal or by a poly-crystal. Typical sizes are 5’’ (125x125 mm) and 6’’ (156x156 mm).

Figure 5 – Examples of crystalline PV cells

Mono-crystalline PV cells come from single-crystal ingot slicing, while Poly-crystalline PV cells come from multi-crystalline ingot slicing. Both require subsequent refinement.

After slicing Silicon wafers are obtained. Further passages are:

- Front contact deposition
- Back contact deposition
- Anti-reflective coating
- Texturing (optional)

6.2.2 PV modules

Solar cells are very fragile and must be purposely protected in a rigid structure, namely a PV module, where a number of PV cells is assembled and connected together in a single body with a transparent front glass. A PV module is thus defined as a complete and environmentally protected assembly of interconnected photovoltaic cells.

The structure of a PV module is called “Sandwich”, because many layers tightly packed are necessary to protect the PV cells and give the necessary mechanical and electrical characteristics (see Figure 6).

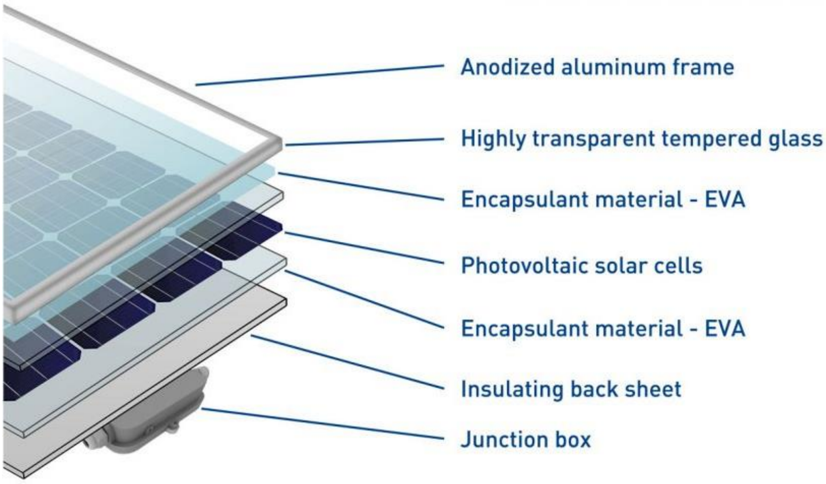


Figure 6 – Typical structure of a PV module

Presently the crystalline solar PV module available in the market has a nominal power that usually is in the range of 300 Wp to 400Wp (sometimes more than400Wp), measured at a specific irradiance and temperature called as Standard Test Conditions or STC (1000 W/m^2, 25 °C, A.M 1.5).

6.2.3 Thin-film technologies

Although the crystalline PV technology is the most widely used, there are also other technologies that are based on the deposition of a thin layer of semiconductor on a front glass. The resulting thickness of this deposit is a few µm and for this reason these products are called Thin-film PV modules. Commercially available thin film modules technologies uses the following materials

- Materials such as Copper-Indium-(Gallium) diselenide (CIS /CIGS) or Cadmium telluride (CdTe)
- Silicon-based thin-film products are represented by amorphous silicon and micro-crystalline Thin-films

The higher costs of these expensive materials are largely compensated by the much lower quantities needed to obtain the photovoltaic conversion.

Uniformity, flexibility and transparency are perhaps the more relevant aesthetic characteristics of thin-film PV technologies. Conversely, their efficiency is normally lower than their wafer-based crystalline counterpart(except for CdTe technologies, which has almost similar efficiency level as that of crystalline silicon).

7 PLANNING OF A SMALL-SCALE SOLAR PV SYSTEM

7.1 Overview

PV modules, composed by several PV cells, are mechanically assembled and electrically connected is series and parallel to form a PV array as shown in Figure 7. The PV array provides all the power coming from the solar conversion, but it cannot be used directly because it is not compatible with the characteristics of the electric appliances and the electric grid.

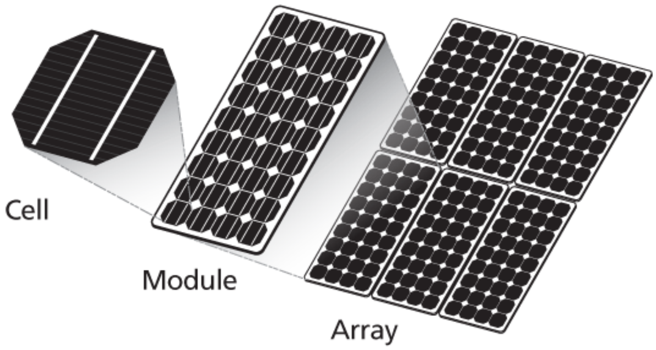


Figure 7 – Passages from the PV cell to the PV array

The DC power coming from the PV array is thus converted in AC power fully compatible with both the home appliances and the public grid. This function is operated by means of specific equipment called Inverter. The inverter is an electronic equipment that performs several functions: mainly it optimizes the electrical operation of the PV array and transforms the DC power into AC power that may be used by the electric appliances or injected into the public grid when necessary.

Beside the inverter there are other equipment aimed to safeguard the grid (Interface protection), to measure the energy produced and exchanged with the grid (Meters) and to sort the power (AC switchgear).

Such PV systems are called “Grid-connected” PV systems or “Grid-tied” PV systems. They make available every kWh that is possible to produce from the sunlight conversion and send it to the internal appliances or to the public grid according to the instantaneous production and consumption.

A number of environmental benefits are also associated to a grid-connected PV system, which are:

- The energy produced is 100% renewable and comes from the Sun
- The plant does not produce any pollutant or any noise, it is fully compatible with the environment
- The energy produced fully replaces the equivalent amount coming from fossil fuels and thus reduces emissions of pollutants, in particular greenhouse gasses in the atmosphere

7.2 Type of installation

Small-Scale Solar PV Systems have a large number of possibilities for installation. The following list gives the main types that are available for mounting a PV array, but each of them has a number of variants. It is also specified if a given type can be building attached (BAPV), building integrated (BIPV) or none of them.

- Ground mounted PV array – Figure 8
- Rows of inclined PV modules on rooftop (BAPV – Figure 9)
- PV modules mounted with the same inclination of the rooftop (BIPV – Figure 10 or BAPV – Figure 11)
- Canopy on rooftop (BIPV or BAPV – Figure 12)
- PV modules on sheds on rooftop (BIPV or BAPV)
- PV façade (BIPV or BAPV – Figure 13)
- Externally integrated PV array (e.g. balconies, balustrades, shutters, awnings, louvres, brise-soleil etc.) (BIPV – Figure 14 and Figure 15)
- PV Canopy (BIPV – Figure 16 and Figure 17 or BAPV)

Figure 8 – Ground mounted PV array

Figure 9 – Rows of PV modules on rooftop

Figure 10 – PV on inclined rooftop (BIPV)

Figure 11 – PV on inclined rooftop (BAPV)


Figure 12 – Canopy on rooftop (BAPV)


Figure 13 – PV façade


Figure 14 – Externally integrated PV


Figure 15 – Externally integrated PV


Figure 16 – PV canopy (BIPV)


Figure 17 – PV canopy (BIPV)

7.3 Power capacity and constraints

7.3.1 Preface

The power capacity of Small-Scale Solar PV Systems is a choice of the Eligible consumer in the range from 1 kW to 2 MW but it is influenced by a number of constraints that limit the upper boundary of its value.

These main constraints are described here below.

7.3.2 Available area

Depending on the type of installation, the available area may be represented by a ground surface, a well oriented roof flap, a rooftop area for a floor mounted PV or a PV canopy, or anyway a suitable space available for any other type of installation. It is important that in the area made available there are no existing equipment that may interfere with the Solar PV System or vice-versa (e.g. HVAC systems, smoke evacuators, chimneys, Lightning Protection System, etc.). According to safety rules and mounting instructions a due distance shall be adopted in order to avoid any detrimental interference.

Special care must be taken in order to avoid any shading on the PV array. Shading may be originated by structures as balconies, walls, railings or surrounding buildings, as well as from vegetation or temporary sources as laundry put to dry.

In case of ground mounted PV arrays or rows on a rooftop, it is also important to avoid or minimize the effects of the reciprocal shading.

7.3.3 PV technology

Although the PV technology does not represent a constraint in itself, it should be considered that in a given available area the maximum power capacity that can installed is limited by the conversion efficiency of the PV modules.

The conversion efficiency of the commercial PV modules can range from less than 10 % of some Thin-film technology to a far more than 20 % of the top rated mono-crystalline model. The ratio between the less efficient and the most efficient is then almost 3:1.

Therefore, when the power capacity is an important target and the space available is limited, the choice most likely will fall on a high performant PV technology, in spite of its presumable higher cost. Conversely, if the space available is larger than necessary, the PV conversion efficiency does not represent a constraint and the choice of the technology may be made by taking into account different criteria (e.g. the cost).

7.3.4 Maximum Connected Capacity

According to the Small-Scale Solar PV Systems Regulations - Electricity & Cogeneration Regulatory Authority (ECRA) – ERD-TA-012 (V02/19), the Maximum Connected Capacity of a Small-Scale Solar PV System to be installed at any Eligible Consumer’s Premise shall not exceed the Connected Load for the consumption account.

7.3.5 Yearly consumption

The Net-Billing is an effective mechanism of compensation for comparing the monetary value of energy exported with the monetary value of the energy imported. This means that every mismatch between solar PV production and internal consumption may be easily managed by the presence of the distribution network. When the solar PV production exceeds the captive consumption the difference is sent to the distribution network, and conversely, when the solar PV production is less than the consumption or is null (evening or in the night) the difference is taken from the distribution network.

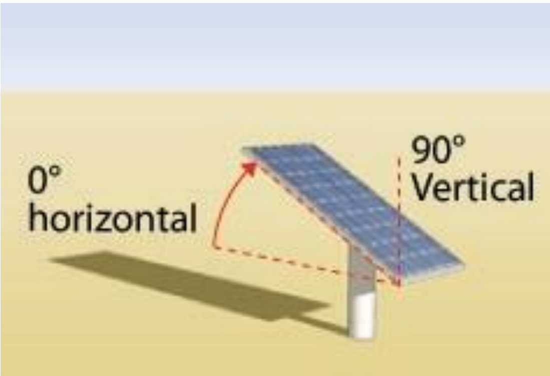
Therefore, at the end of a period (month, year) the energy meter at the Exit point registers an amount of kWh that has been absorbed from the network and an amount of kWh that has been injected toward the distribution network. The net billing mechanism in its simplest version makes the monetary difference between input and output. In case of any surplus energy produced by the solar PV

system and injected to the grid, a financial valuation will take place and the amount will be transferred and deducted from the next billing cycle.
However, the Net-Billing is economically viable if in the medium-long term the energy produced does not exceed the energy consumed. In other words, if a PV system is oversized in terms of energy production, the Eligible consumer could never use all the energy its Solar PV System produces.

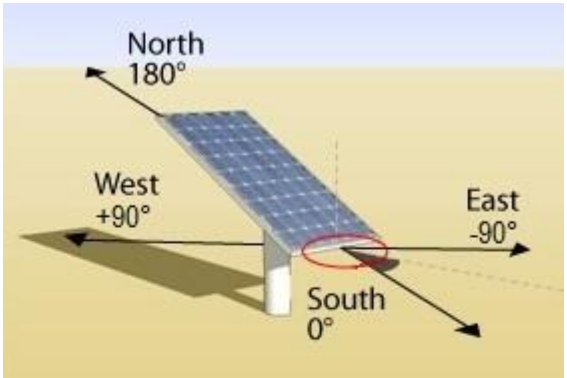
7.4 Orientation and Inclination of PV modules

There are several factors to be accounted for when planning to install a Small-Scale Solar PV System on a rooftop. By considering the geometry of the PV array, these factors are (see Figure 18):

- Orientation of PV modules to the sun;
- Inclination (tilt) angle of PV modules; and
- Shadowing from objects or other buildings.



Inclination (tilt) of a PV module



Orientation (azimuth) of a PV module

Figure 18 – Orientation and inclination of the PV modules

The favourable orientation (azimuth) for fixed solar cells in the KSA throughout the year is South (0° S) with an inclination (tilt) of about 24° with respect to the horizontal plane. This allows an average annual irradiation on a horizontal plane of about 2200 kWh/m²yr for KSA when both the direct and diffused radiation are considered, which means about 1600÷2000 kWh/yr per kWp installed.

Table 1 – Typical figures to be considered for the assessment of a Small-Scale Solar PV System in the KSA

Optimal orientation of the PV modules (azimuth)	0° South
Optimal tilt of the PV modules	24-26° with respect to the horizontal plane
GHI (Global Horizontal Irradiation) – Average value in the KSA	2,200 kWh/m²yr
Range of producible energy – Average value in the KSA	1600 - 2000 kWh/yr per kWp installed

Small variations around these values do not significantly affect the production. For instance, an energy reduction not greater than 5% can be noticed by maintaining a South orientation and varying the tilt from 5° (this value to be raised to 10° to allow a better cleaning) to 40°. It is also possible to stay below a 5% loss by varying the azimuth of the PV modules from -60° to +60°, if the tilt is kept at 24°.

It is essential to avoid any shadows on the PV modules, because this can cause a substantial drop in the system performance. In contrast to solar thermal collectors for water heating, any shadows on a PV array causes a significant reduction of the power produced. Furthermore, especially in KSA, where the beam fraction of the solar radiation is high, partial shadowing on PV modules causes strain on shadowed PV cells which may, in turn, lead to local temperature rising (hot-spots) and may thus compromise the durability and safety of these components.

It is important that the PV modules are kept clean and to avoid deposits of dirt and dust, since these reduce the efficiency of these components. In KSA there are regions prone to dusty desert environments and frequent dust storms, therefore it is recommended to clean the PV modules so as to avoid dust, sand and dirt accumulation. A flatter position of PV modules may increase the deposits on these and make their cleaning and washing more difficult, especially in case of large surfaces. It is therefore recommended to adopt a minimum tilt angle of at least 10°.

In a building, PV modules are usually installed on the roof in order to reduce shadowing and also to exploit surfaces often left unused. When possible, PV modules may be integrated in the building structure as Building Integrated Photovoltaic (BIPV) systems; these are frequently adopted to mitigate the visual impact of PV systems. Although often attractive from the point of view of aesthetics, PV facades (tilt = 90° or similar) are not recommended from an energy efficiency point of view, because their production is approximately 50% less than when optimally positioned.

7.5 Shading

A solar PV plant is composed by a number of PV modules (PV array) placed on a given area. Often, the hemisphere above the PV array is not free of obstructions and therefore in most cases both the direct and the diffuse solar irradiation are affected by constructions, hills, vegetation, walls or any other obstacles that may be found in the surroundings. When one of such elements intercepts the direct sun rays, a shadow appears on a portion of the PV array and thus a problem related to shading might arise.

It should be noticed that in many cases it is difficult to avoid shading, especially in urban areas or also in rural areas with vegetation or uneven ground. However, it is important to exclude situations where shading may compromise the energy yield of the solar PV plant or, worse, endanger the integrity of the PV modules.

A qualitative analysis of the shading on a PV array may be done by drawing the solar paths on a diagram where x-axis represents the azimuthal orientation clockwise (0° = North, 90° = East, 180° = south, 270° = West) and the y-axis represents the sun elevation. Sun paths are usually drawn for each month of the year but those symmetric are considered equivalent.

Obstructions are thus inserted in the diagram considering their elevation angle and their azimuthal wideness. All obstructions affect the diffuse radiation, but the most important are those that intercept the direct radiation, namely in the diagram are placed on sun paths.

As an example, in Figure 19 it is shown the monthly sun paths in Riyadh and the two areas where shading is allowed and where it should be avoided.

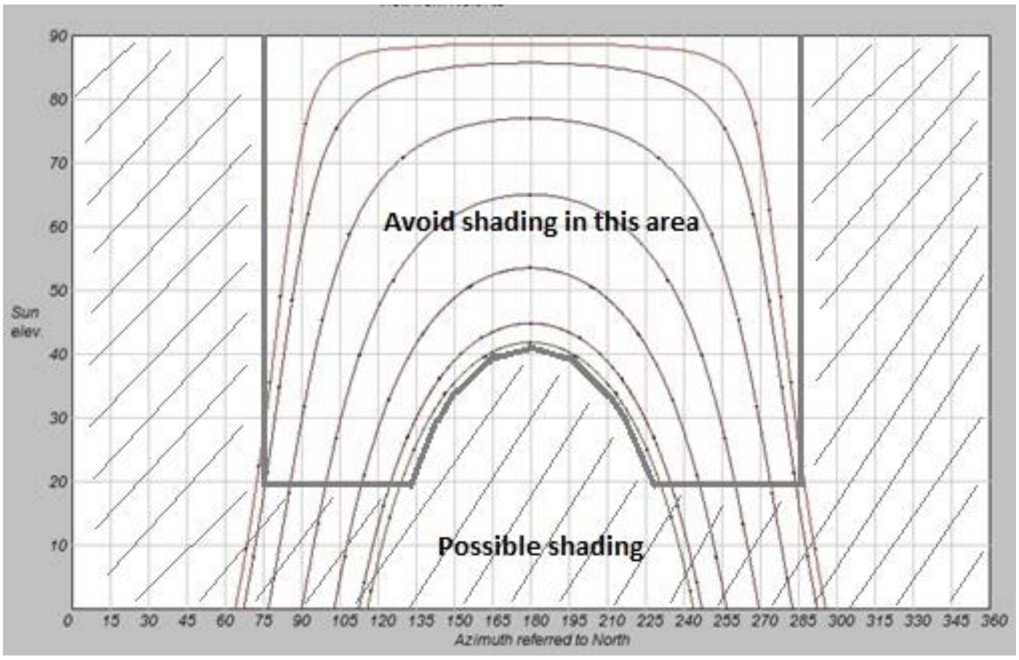


Figure 19 – Solar paths and recommended maximum shading

The curve shown in Figure 19 shall be strictly followed in case of obstructions that may shade a portion of the PV array because they may compromise the integrity of the PV modules. Conversely, in other cases where the PV array is highly inclined or even vertical (facades) derogation may be accepted.

7.6 Solar PV Equipment

7.6.1 How a grid-connected Solar PV System works

A typical Solar PV System producing electricity has to be connected to a distribution panel and is usually composed of:

- Solar PV modules and their interconnections;
- Inverter(s);
- Metering System;
- Interface Protection; and
- Electrical and mechanical installations (structures, cables and electric panels).

In Figure 20 it is shown a simplified diagram of a grid connected solar PV plant, where the electric loads are represented by domestic appliances. The same diagram applies also to larger PV plants installed, for instance, on schools, factories or malls. Most likely, in these cases the PV plant is larger, and the electric loads change considerably.

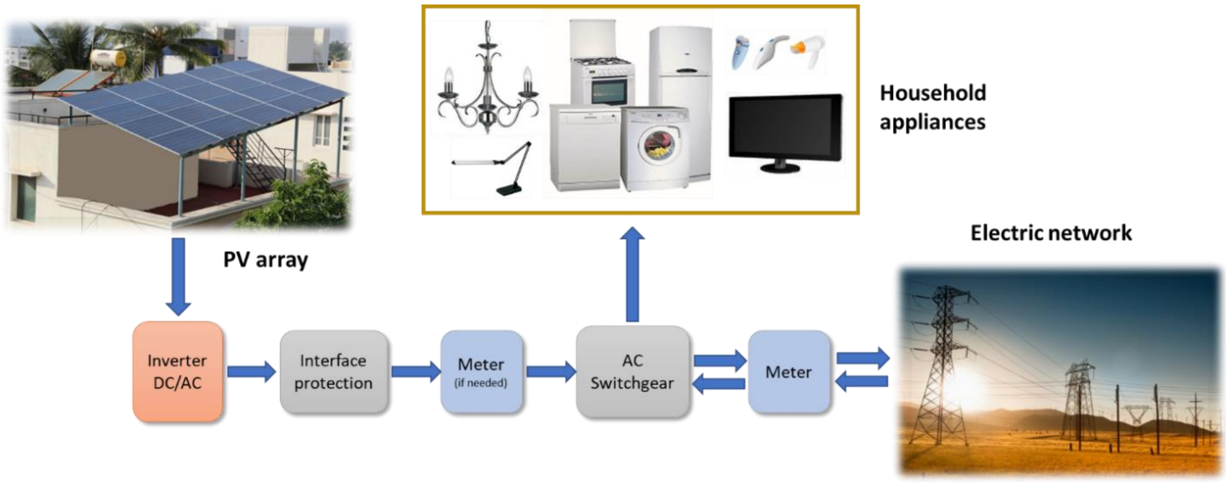


Figure 20 – Block diagram of a grid-connected solar PV plant for a household

In Figure 20 it is possible to notice that an exchange of energy from and to the distribution network is present. When the power produced by the Solar PV System is higher than the electric consumption, the power in excess is sent to the distribution network. Conversely, when the power produced by the Solar PV System is not enough to cover the captive consumption, the difference is taken from the distribution network.

The way the solar PV plant is connected to the network is explained in the connection schemes shown in the Technical Standards for the Connection of Small-Scale Solar PV Systems to the LV and MV Distribution Networks of SEC

The Standards also specify another important element, the Interface Protection, which prevents the current of the plant from being injected into the network whenever a faulty event is detected on the latter. This IP protection may also be included in the inverter.

The switch on which the Interface Protection acts (Interface Switch) may also be used to disconnect the plant for maintenance purposes, without causing any shortages on the existing loads.

Consultants and Contractors shall refer to the detailed instructions and requirements provided by the suppliers that shall be fulfilled during the installation operation and maintenance of the Solar PV System.

7.6.2 Solar PV modules

Solar PV modules can consist of PV cells of different technologies as presented in 6.2. In commercial and non-concentrating applications, single-crystalline and multi-crystalline cells achieve the maximum efficiency while thin-film technology needs more area to produce the same power than their crystalline counterparts. Most manufacturers often guarantee a lifetime of 25 years or more, but they seldom take into account harsh conditions like those in KSA. Furthermore, manufacturers indicate that PV modules undergo a loss of performance over time and therefore, a guaranteed efficiency is provided (e.g. usually 90 % after 10 years and 80 % after 25 years). However, it is advisable to have a workmanship warranty of at least 10 years and, given the harsh conditions in KSA, also a third party insurance backing for medium-large size plants (e.g. greater than 1 MW).

In general, bypass diodes should be installed in order to prevent reverse bias in the PV modules and to avoid consequent hot spot heating.

7.6.3 Inverter

The inverter converts the DC current produced by PV modules into AC current that can be used directly in the house/premises and/or injected into the external network. Ideally, the inverter should be located close to the photovoltaic modules to avoid losses, but this cannot always be possible because of the harsh outside conditions. High temperatures and dust in particular, require special caution in order to avoid any damage or performance reduction of the equipment.

It is therefore recommended to verify that the highest temperature to which the inverter can be exposed in summer does not cause any damage to it or reduce its life. Moreover, it is necessary to avoid high temperatures that may trigger any protection system aimed to reduce the internal temperature of the inverter by reducing its power (de-rating protection). If these conditions are not satisfied by mounting the inverter outside it is recommended to install the inverter in a safe room with enough ventilation and air conditioning, if necessary.

The inverters shall be provided with an IP65 enclosure for outdoor application and IP54 enclosure for indoor application. In this latter case, lower protection grades shall only be permitted if the characteristics of the room are properly conceived to protect the equipment (e.g. air-conditioned rooms with means to avoid dust penetration). Whatever the case may be, the inverter should be able to withstand the maximum temperatures with effective heating dispersion and without power de-rating for temperatures lower than 50 °C. The efficiency of the Inverter should be greater than 95 % with a general guarantee of at least 10 years.

7.6.4 Metering System

To measure the electricity generated by the renewable generation unit and electricity consumed by the house/building, two bidirectional energy meters must be installed:

1. The first meter supplied and installed by SEC in the exit Point measures the power injected to the Distribution Network and the energy absorbed from the Distribution Network. ("Main electricity meter"). This meter is already present in existing installations; however it shall be substituted by a smart meter if this has not already been done.
2. The second meter supplied and installed by SEC if the Power Capacity of the Small-Scale Solar PV System exceeds 100 kW, and it measures the electricity generated by the photovoltaic system ("Solar PV System meter").

During the connection process, SEC will inspect the Solar PV System before the metering system can be installed. The inspection aims to ensure that the Solar PV System complies with the Standards, with the wiring regulations and with the safety rules.

7.6.5 Other equipment

All the components and equipment used in a Solar PV System shall comply with applicable standards and laws in force in KSA. Any component or equipment that may introduce harmful or hazardous conditions shall be rejected.

All components and equipment are chosen adequately in order to assure their integrity and operation for a long lasting period. All equipment should be of an IP rating suitable for the location and this particularly applies to:

- Cables and connectors exposed to sunrays (UV in particular), external temperature and other weather conditions. This equipment is to be certificated for their application (e.g. solar cables). In DC circuits single-wire cables should be used with different colours for the two poles.
- Switchgears and controlgear assembly shall be properly protected against temperature, sunrays (UV in particular), dust, salinity and all other weather conditions present on the site. Installation in a safe room is recommended. Their compliance to applicable standards shall be properly certificated (SASO IEC 61439 series).
- PV string combiner boxes shall be properly protected against temperature, sunrays (UV in particular), dust, salinity and all other weather conditions present on the site. Their location shall be visible without obstacle to their inspection and replacement of components (e.g. fuses). Their compliance to applicable standards shall be properly certificated (SASO IEC 61439 series where applicable).

7.7 Compliance of the solar Small-scale Solar PV system

The Small-scale Solar PV System that is to be connected to the distribution network must comply with the requirements of the *Technical Standards for the Connection of Small-Scale Solar PV Systems to the LV and MV Distribution Networks of SEC*. The equipment of the Small-scale Solar PV Systems, which include the PV modules, the PV inverters and the Interface Protections, are to be certified according to the compliance requirements defined by the product standards listed in the *Technical Standards for the Connection of Small-Scale Solar PV Systems to the LV and MV Distribution Networks of SEC*. The certification document will be requested by SEC during the connection process.

8 SMALL-SCALE PV SYSTEMS CONFIGURATION AND SIZING

8.1 PV system architectures

8.1.1 Preface

The Solar PV System shall be designed and erected in accordance with the relevant and applicable international standards, in particular IEC 60364 and SASO IEC 62548 as concerns the Low Voltage AC and DC sections respectively.

Technical choices shall not be in contrast with the local technical rules in force in KSA.

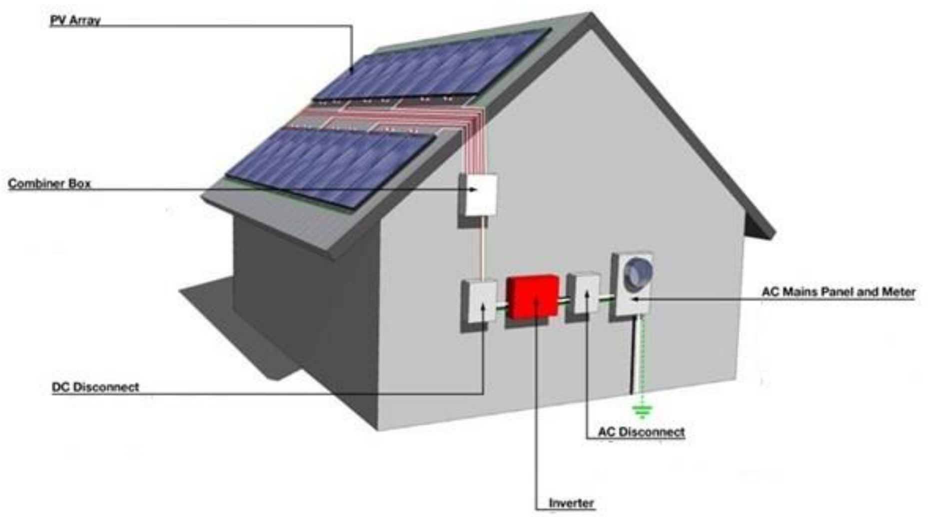


Figure 21 – Small Scale Solar PV System

(Note: PV equipment is schematically shown as installed outside the building only for representation purposes)

8.1.2 String Arrangement

Solar PV modules will be connected in series to form a *PV string* (or more simply a string):

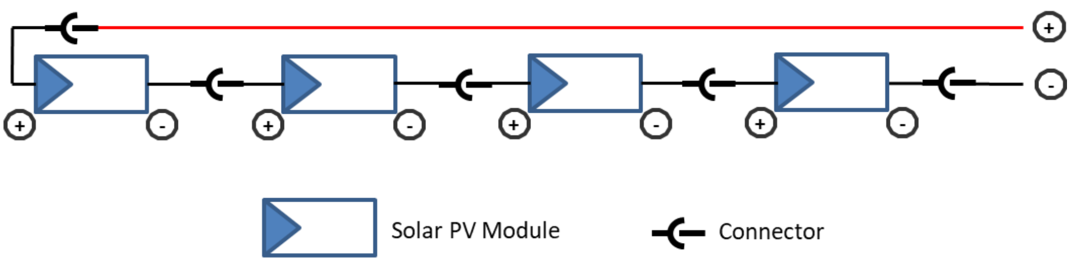


Figure 22 – PV modules connection to form a string

The parallel combination of more strings, or also only one string for small Solar PV Systems, which converge to the same inverter form a *PV Array*. Electrical subsets of a PV Array formed by parallel connected PV strings are possible, and in that case these are defined as *PV Sub-Arrays*.

The diagrams in Figure 23 and Figure 24 show examples of the basic electrical configurations of single string and multiple parallel strings respectively.

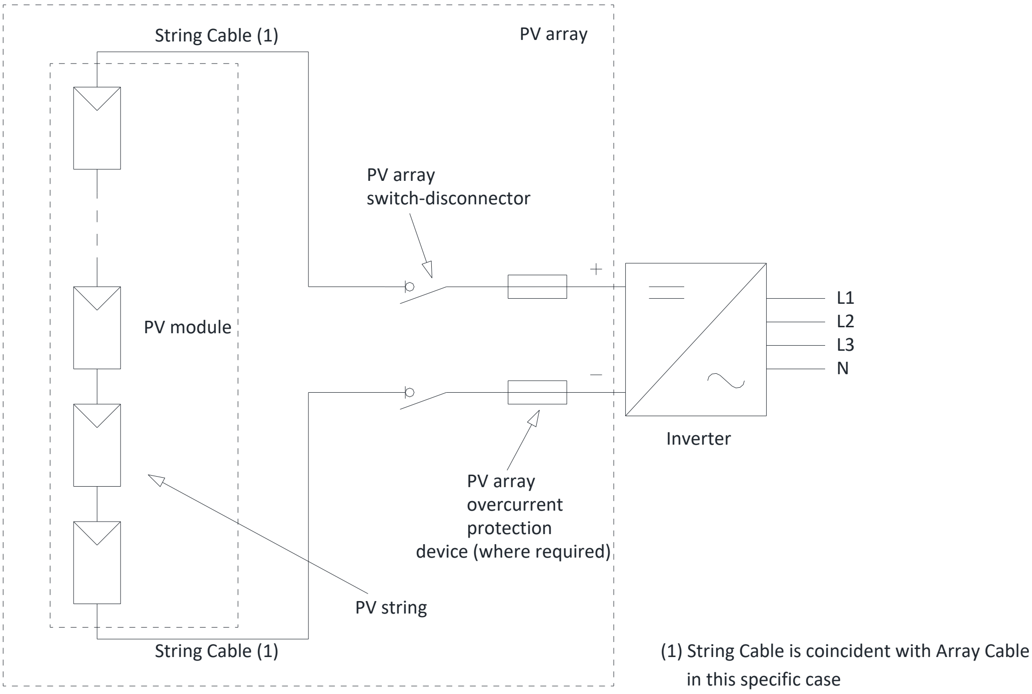


Figure 23 – PV array diagram – Example of a single string

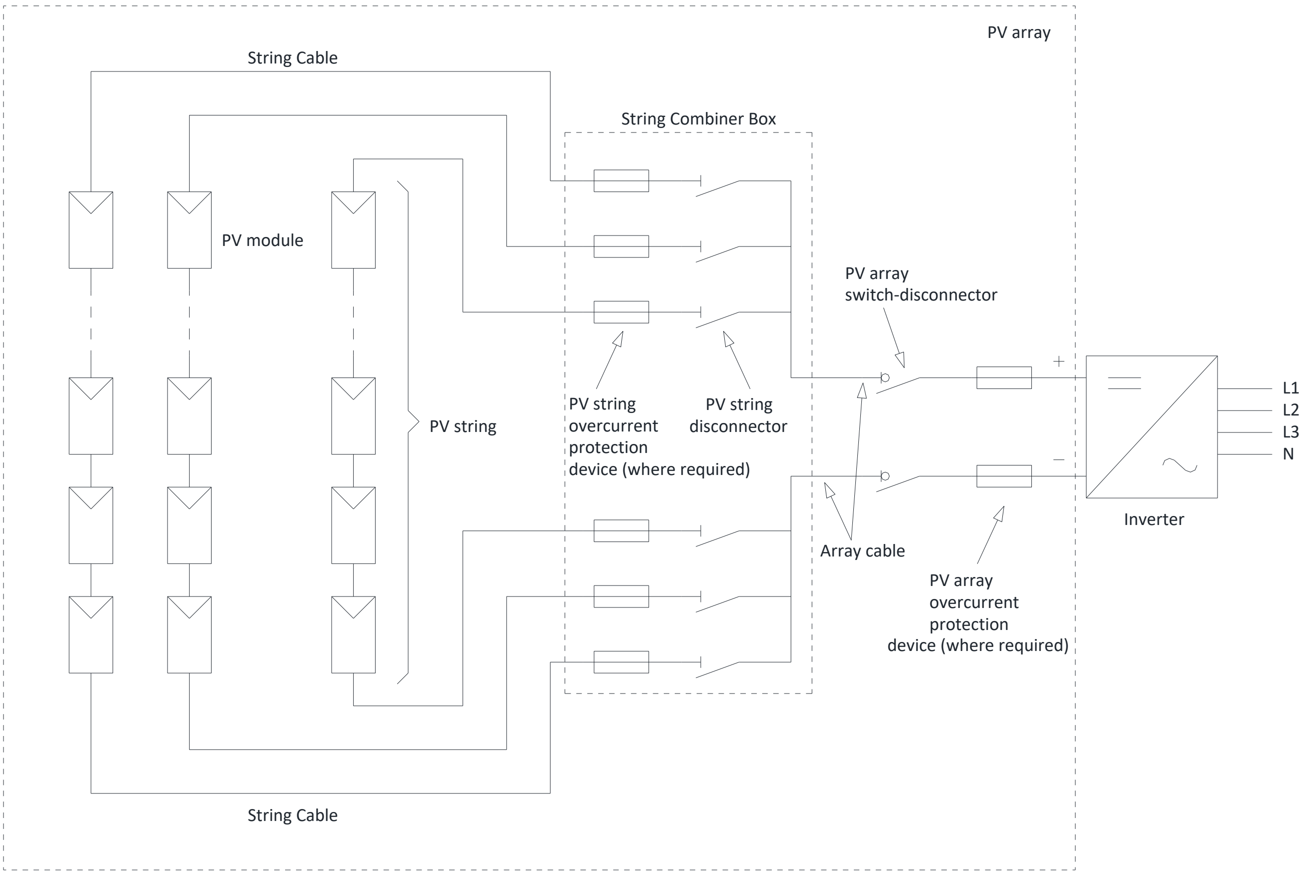


Figure 24 – PV array diagram – Example of multiple parallel string combination

8.1.3 Series-parallel configuration of modules and strings

All PV strings within a PV array connected in parallel are to be of the same technology and have the same number of series connected PV modules. In addition, all PV modules in parallel within the PV array shall have similar rated electrical characteristics including short circuit current, open circuit voltage, maximum power current and maximum power voltage and rated power (all at STC).

It is important that the characteristics of any array or sub-array be fully compatible with the input characteristics of the inverter used. This in particular applies to:

- Rated power at STC;
- Minimum and maximum voltage at any operation condition (solar radiation and air temperature); and
- Maximum system voltage.

Refer to 8.2.1 for details on how to undertake these checks when selecting the correct inverter.

8.1.4 Use of inverters with single and multiple DC inputs

PV arrays are often connected to inverters with multiple DC inputs. If multiple DC inputs are in use, overcurrent protection and cable sizing within the various sections of the PV array(s) are critically dependent on the limiting of any back-feed currents (i.e. currents from the inverter out into the array) provided by the input circuits of the inverter (see 8.3.2 for details).

Where an inverter input circuit provides separate maximum power point tracking (MPPT) inputs, the overcurrent protection of the sub-array connected to the inputs shall take into account any back-feed currents. Each PV section connected to an input must be treated as a separate PV sub-array. Each PV array or sub-array shall have a switch-disconnector to provide isolation of the inverter.

8.1.5 DC/AC converters (Microinverters) in combination with PV modules

Microinverters are electrically connected to PV modules through direct wirings and may be used as:

- Permanently mounted close to the PV module but not mounted to or in direct contact with the module backsheet (also called Detached Microinverters). DC wiring are thus accessible to service personnel although is deemed to be not user-accessible.
- Permanently mounted to the PV module’s backsheet for both electrical and mechanical means of connection (AC modules).

Differently from classical PV arrays, in PV systems that use microinverters the connections in the array are made by using one or more AC parallel wiring systems (AC bus).

Instructions of manufacturers shall be applied especially as regards bonding/earthing of microinverters and in order to avoid overloads on AC wiring. In particular, AC cables shall have a proper voltage rate and, unless they are adequately protected, they shall be resistant to high temperatures, UV rays and other possible mechanical stresses.

In case of detached microinverters, attention has to be given to the characteristics of DC connectors when used as a means to disconnect the DC circuit. When not rated to disconnect under load, all the necessary precautions have to be taken before disconnecting them (e.g. covering of the module).

8.1.6 Mechanical design

Support structures and module mounting arrangements shall comply with applicable building codes regulations and standards and module manufacturer's mounting requirements[1].

Provisions should be taken in the mounting arrangement of PV modules to allow for the maximum expansion/contraction of the modules under expected operating temperatures, according to the manufacturer's recommendations. Similar provisions should be taken for other applicable metallic components, including mounting structures, conduits and cable trays.

The PV array support structures shall comply with local standards, industry standards and regulations with respect to loading characteristics.

PV modules, module mounting frames, and the methods used for attaching frames on buildings or on the ground shall be rated for the maximum expected wind speeds in KSA according to local codes.

In assessing this component, the wind speed observed (or known) on site shall be used, with due consideration to wind events (cyclones, tornadoes, hurricanes, etc.). The PV array structure shall be secured in an appropriate manner or in accordance with local building standards.

Wind force applied to the PV array will generate a significant load for building structures. This load should be accounted for in assessing the capability of the building to withstand the resulting forces.

Module mounting frames, and the methods used for attaching modules to frames and frames on buildings or on the ground, shall be made from corrosion resistant materials suitable for the lifetime and duty of the system, e.g. aluminum, galvanized steel, zinc-coated steel, etc.

Aluminum, when used, shall be anodized to a thickness and specification suitable for the location and duty of the system. Corrosive gases such as ammonia, in farming environments also need to be contemplated.

Care shall be taken to prevent electrochemical corrosion between dissimilar metals. This may occur between structures and the building and also between structures, fasteners and PV modules.

Stand-off materials shall be used to reduce electrochemical corrosion between galvanically dissimilar metal surfaces; e.g. nylon washers, rubber insulators, etc. Manufacturer's instructions and local codes should be consulted regarding the design of mounting systems and any other connections such as earthing systems.

[1] As mentioned in the *Guidelines that inform customers and installers in order to connect a solar PV system to distribution networks,* the Consumer shall be responsible for observing or referring to the applicable laws and regulatory requirements that regard the mechanical and civil design related to the construction of the Small-scale Solar PV System. Although some details regarding the mechanical design are required at the Design Evaluation and Approval Stage, these details are only informative. It is not the responsibility of SEC to check nor to approve the mechanical design of the PV systems, the mechanical and fire safety of the building without or with the PV systems, as well as any issues that regard the compatibility of the PV systems with the aesthetic rules or regulations in force, which shall be the role of the Municipality or of any other governmental institutions deputed to manage the above mentioned duties and responsibilities.

8.2 Solar PV system sizing

8.2.1 Selection of inverters

The selection of the inverter and of its size is carried out according to the Solar PV System rated power it has to manage. The size of the inverter and therefore the active power which can be injected into the Consumer's installation can be determined starting from a value of about 90 - 95 % of the rated power of the Solar PV System, as calculated at STC. This ratio keeps into account the loss of power of the PV modules under the real operating conditions (working temperature, voltage drops on the electrical connections,…) and the efficiency of the inverter, but does not neglect the fact that the generated power from the PV modules can exceed the rated value at STC in some favourable conditions (high irradiance and temperature not too high).

This ratio depends also on the methods of installation of the modules (latitude, inclination, ambient temperature, etc.…) which may cause a variation in the generated power.

The need for reactive power as defined in the *Technical Standards for the Connection of Small-Scale Solar PV Systems to the LV and MV Distribution Networks of SEC* shall also be carefully considered in the choice of the rated power of the inverter.

For the correct sizing of the inverter, the following parameters should be considered:

• DC side:

- rated power and maximum power;
- rated voltage and maximum admissible voltage;
- range of variation of the MPPT voltage under standard operating conditions;
- maximum input current per MPPT;

• AC side:

- rated power and maximum power which can be continuatively delivered by the inverter, as well as the field of ambient temperature at which such power can be supplied;
- rated current supplied;
- maximum delivered current allowing the calculation of the contribution of the Solar PV System to the short-circuit current;
- maximum voltage distortion and power factor;
- maximum conversion efficiency;
- efficiency at partial load and at 100% of the rated power (so called "European efficiency" or efficiency diagram)

Moreover, it is necessary to evaluate the rated values of voltage and frequency at the AC output and of voltage at the DC input of the inverter.

The voltage and frequency values at the AC output depend on the rated values of the SEC distribution network, which are defined in the *Technical Standards for the Connection of Small-Scale Solar PV Systems to the LV and MV Distribution Networks of SEC*.

As regards the voltage at the DC input, the extreme operating conditions of the Solar PV System shall be assessed in order to ensure a safe and productive operation of the inverter.

Some conditions shall be checked, by comparing the following rated values of the inverters:

- V_{MAX} (Inverter): maximum input voltage which can be withstood by the inverter

- $V_{MPPT\ min}$ (Inverter): minimum input operating voltage admitted by the inverter
- $V_{MPPT\ max}$ (Inverter): maximum input operating voltage admitted by the inverter

With the following severe operating conditions of the Solar PV System (in particular, these checks are carried out for strings):

- $V_{oc\ max}$ (PV string) at 0°C: open circuit voltage of the Solar PV string, in correspondence with the minimum operating temperature expected for the PV modules at the installation site. A conventional temperature of 0°C is considered on the safety side (8.3.1)
- V_{min} (PV string) at 80°C: voltage of the Solar PV string with standard irradiance, in correspondence with the maximum operating temperature expected for the PV modules at the installation site
- V_{max} (PV string) at 0°C: voltage of the Solar PV string with standard irradiance, in correspondence with the minimum operating temperature expected for the PV modules at the installation site. A conventional temperature of 0°C is considered on the safety side (8.3.1)

More specifically, the conditions to be checked are four, namely:

A) the Maximum Open-Circuit (no-load) Voltage of the string, at minimum expected working temperature (T = 0 °C), must not exceed the maximum input DC voltage of the inverter:

1) $V_{oc\ max}$ (PV string) at 0°C ≤ V_{MAX} (Inverter)

But also:

2) $V_{oc\ max}$ (PV string) at 0°C ≤ V_{MAX} (PV modules)

B) the voltage at the MPP of the string, calculated at the maximum operating temperature (T = 80 °C) with an irradiance of 1000 W/m^2, must not be smaller than the inverter minimum working voltage at MPPT:

1) V_{min} (PV string) at 80°C ≥ $V_{MPPT\ min}$ (Inverter)

C) the voltage at the MPP of the string, calculated at the minimum operating temperature (T = 0°C) with an irradiance of 1000 W/m^2, must be smaller than the maximum inverter working voltage at MPPT

1) V_{max} (PV string) @ 0°C ≤ $V_{MPPT\ max}$ (Inverter)

Consultants and Contractors who are in charge of designing the Solar PV System, should be aware that proper tools exist, developed by the inverter manufacturers and typically available on the web, to guide the engineer to a correct choice and carry out the above checks.
However, if this is done by hand calculation, the above voltages can be yield in the way described hereinafter:

- Maximum Open-Circuit (no-load) Voltage $V_{oc\ max}$ of the PV string

The open-circuit voltage of a Solar PV module is higher at low temperatures. The maximum open-circuit voltage can be calculated from the module open-circuit voltage and by knowing the PV module temperature coefficient. The lowest expected temperature at the installation site must be considered:

$$V_{oc\ max} = N_{mod} \times [V_{oc} + \beta \times (T_{min} - 25)]$$

Where:

$V_{oc\ max}$: Maximum PV string open circuit voltage at min T (0°C)
V_{oc}: Open-Circuit (no-load) voltage of PV module
N_{mod} : number of modules in series of the string under verification (and then of each string of the same array)
β : Temperature coefficient of Open-Circuit (no-load) voltage (V/°C)
(T_{min} - 25): Variation between minimum expected cell temperature (0 °C) and STC (25 °C)

- Minimum MPP Voltage of the PV string - V_{min}

The operating voltage of a Solar PV module is lower at high temperatures. The minimum PV module voltage can be calculated from the MPP voltage, by using the module open-circuit voltage and the temperature coefficient. The highest expected operating temperature must be considered.

$$V_{min} = N_{mod} \times [V_{MPP} + \beta \times (T_{max} - 25)]$$

Where:
V_{MPP} : Voltage of PV module at maximum power
V_{oc}: Open-Circuit (no-load) voltage of PV module
N_{mod} : number of modules in series of the string under verification (and then of each string of the same array)
β : Temperature coefficient of Open-Circuit (no-load) voltage (V/°C)
(T_{max} - 25): Variation between maximum expected cell temperature (80°C) and STC (25°C)

- Maximum Temperature

Approximately $T_{max} = T_{air\_max} + (NMOT - 20) / 0.8$
Where:
T_{max} : maximum expected cell temperature
T_{air_max} : maximum expected air temperature
NMOT: Nominal Module Operating Temperature of the PV module as defined by SASO IEC 61215 (to be retrieved from PV module data sheet)
Assuming a maximum expected temperature of 50°C and typical values of 45°C for NMOT of crystalline silicon PV modules, a T_{max} of 80°C can be reasonably assumed in the checks.

- Maximum MPP Voltage of the PV string - V_{max}

The voltage is higher at low temperatures. The maximum PV module voltage can be calculated from the MPP voltage by using the module open-circuit voltage and the temperature coefficient. The lowest expected cell operating temperature must be considered.

$$V_{max} = N_{mod} \times [V_{MPP} + \beta \times (T_{min} - 25)]$$

Where:
V_{MPP} : Voltage of PV module at maximum power
V_{oc}: Open-Circuit (no-load) voltage of PV module
N_{mod} : number of modules in series of the string under verification (and then of each string of the same array)
β : Temperature coefficient of Open-Circuit (no-load) voltage (V/°C)
(T_{min} - 25): Variation between minimum expected cell temperature (0 °C) and STC (25 °C)

From the above factors the number of PV modules to be connected in series for a PV strings shall be determine based on the conditions as per 8.2.1A, B & C.
Regarding the choice of the optimal architecture for the Solar PV System, several options are available. Some possible situations are illustrated hereinafter, which cover the majority of the cases, but not necessarily all. Specific situations, due to the conditions at site evaluated during the first visit and site assessment, shall be carefully analysed by the Consultants and Contractors.

A) Solar PV Systems with Single inverter (also called «Central Inverter»): this is a case that can be verified both for small installations and for large PV fields. The main characteristics and considerations are:

- Cheapest and most applied solution for small Solar PV Systems (say up to 10kW)
- Single inverter for the whole PV array, therefore possible only when the PV modules are of the same type and have the same azimuth and tilt
- Problems with shading and overcurrent protection increased, as an issue in one string affects the whole array
- Shutdown of the whole PV generator in case of failure of the inverter
- Need for blocking diodes in the string to avoid current circulation due to mismatch

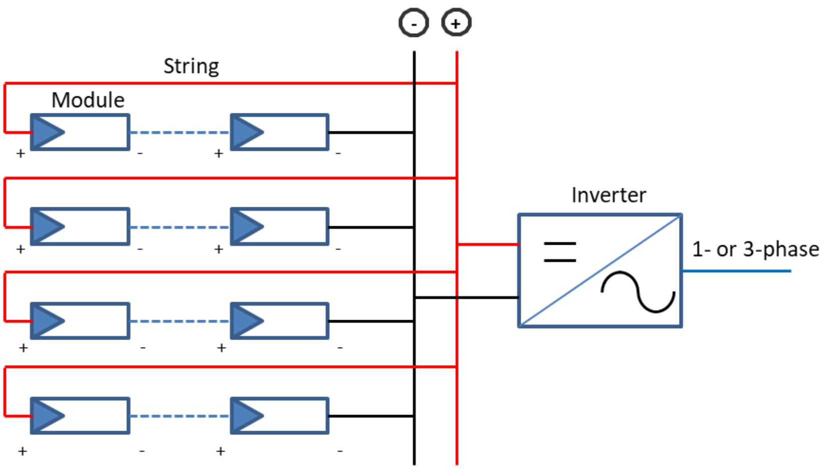


Figure 25 – Solar PV System with single inverter

B) Solar PV Systems with String inverter:

- Each string is connected to its own inverter (string conversion)
- Each string operates according to its own Maximum Power Point (MPP), therefore this can be used in case of non-homogeneous conditions in terms of orientation and azimuth of the PV modules
- Coupling between PV modules and inverters improved
- Losses due to shading reduced, as a problem in one string does not affect the rest of the system
- Overcurrent protections and blocking diodes can be omitted, i.e. diode losses are cancelled
- Efficiency and reliability improved
- More expensive than the Single inverter solution

- Number of AC output increased (need for mode circuit breakers on the AC panel)

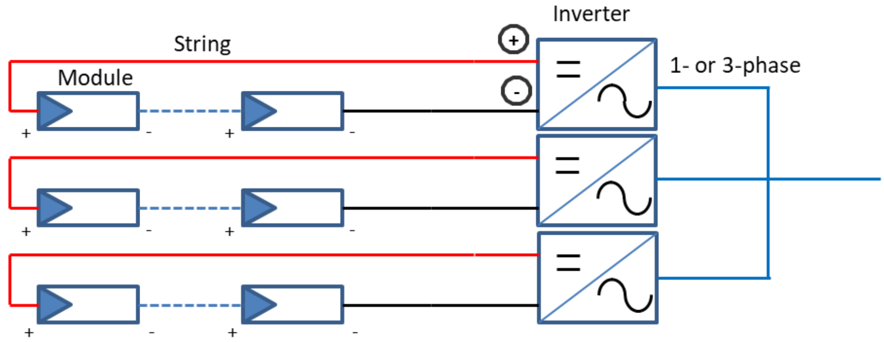


Figure 26 – Solar PV System with string inverters

C) Solar PV System with Multi-String inverter:

- More than one string is connected to the same inverter
- No need to use string combiner boxes
- Inverter provided with more than one MPPT can be used (management of single string independently of the others, e.g. because made of a different number of modules - different module layout or tilt – shading on one string)
- Only one AC output
- Losses due to shading limited only to the PV sub-array connected to the MPPT input of the inverter were also the shaded string is connected
- Overcurrent protections and blocking diodes can be omitted as normally built in the inverter
- More expensive than the Single inverter solution

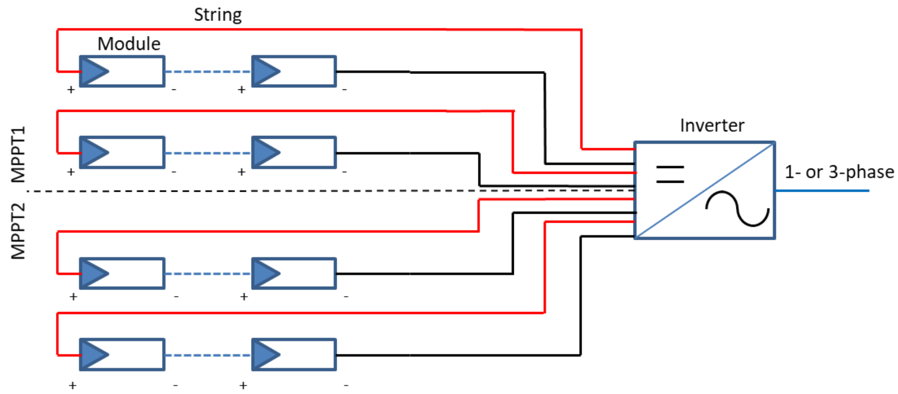


Figure 27 – Solar PV System with Multi-string inverter

D) Multi inverter Solar PV Systems:

- PV field divided into several arrays
- Still possibility to group string with similar characteristics (number of modules, layout)
- Installation and maintenance cost reduced (lower number of inverters with respect to string inverters)

- Loss of production of only one PV array, in case of inverter failure

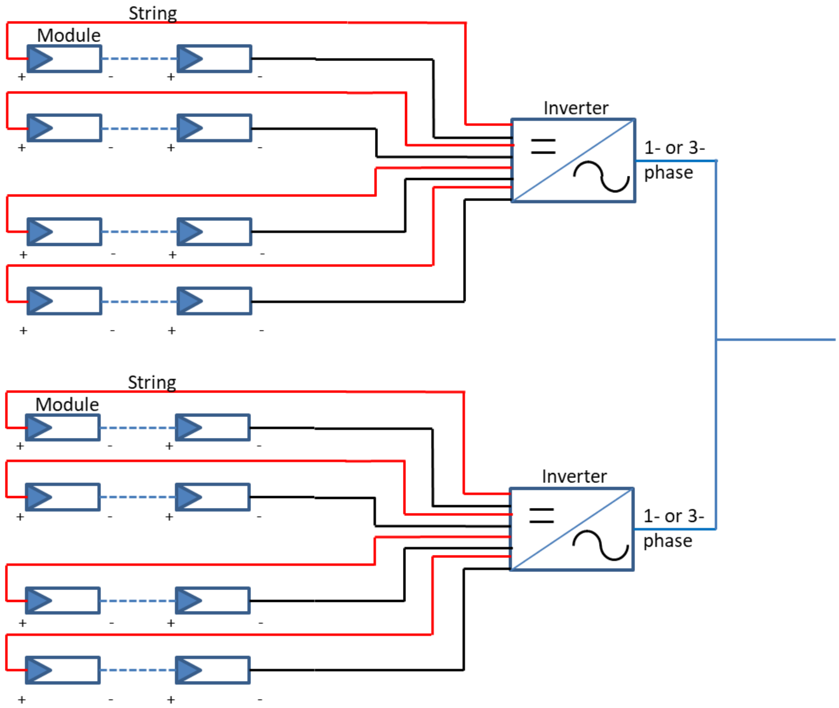


Figure 28 – Multi inverter Solar PV System

8.2.2 Cable types and selection

Some indications for the selection of the correct section of both DC and AC cables to be used in Solar PV Systems are given here. However, it is not the scope of this Guide to give a comprehensive dissertation on concepts on which both Consultants and Contractors should already be aware, as these are similar to those applicable to load demand installations. Therefore, the focus is mainly on the DC side of a Solar PV System, which can be dealt with less frequently by engineers as it is less common compared to AC systems.

8.2.2.1 DC side cables

The cables of the DC side of a Solar PV System must have a rated voltage suitable with the maximum DC voltage of the system itself, which shall be calculated at the conditions stated in 8.3.1 and already discussed in 8.2.1 for the verification of conditions in the choice of inverters. Considering that this voltage cannot exceed 1000 Vdc/1500Vdc, use of cables with maximum DC voltage of 1800 Vdc is recommended.

As every other equipment used on DC side (PV modules, junction boxes or cabinets), up to the DC terminals of the PV inverter, cables shall be class II or equivalent insulation, so as to minimize the risk of earth faults and short-circuits (IEC 60364-7-712) as well as to protect against electric shock (SASO IEC 62548).

With reference to Figure 23 and Figure 24 the cables on the DC side can be divided into:

- String cables, which connect the PV modules to a combiner box or directly to the inverter. These are commonly known as *Solar Cables*. These do not include the rear cables which each PV module is already provided with, which are chosen by the manufacturer and which guarantee the connection between PV modules. However, also these shall comply with the same requirements for the string cables;
- Cables to connect the combiner boxes to a DC panel or to the inverter (e.g. Array cables of Figure 24). Use of *Solar Cables* is recommended in this case too, as these cables have normally similar laying conditions with respect to those above described.

The string (Solar) cables, similarly to the cables connecting the modules, are normally fastened in the rear part of the same modules, where the temperature may reach also 80°C in countries like KSA. As a consequence, in addition to the electrical characteristics, the string cables used in a Solar PV System must be able to withstand, for the whole life cycle of the system (at least 20 years), harsh environmental conditions, particularly in terms of high temperatures and ultraviolet radiations.
The characteristics of cables which suit the above requirements and available on the market are the following:

- Conductor: tinned copper, flexible, class 5
- Insulation: special compound cross-linked HT-PVI (Low Smoke Zero Halogen (LS0H))
- Sheath: special compound cross-linked HT-PVG (Low Smoke Zero Halogen (LS0H))
- suitable for applications in equipment with protective insulation class II. They are inherently short-circuit and earth fault proof protection
- UV resistant
- Colour: black, red, blue

Functional characteristics

- Nominal operating DC voltage: 1500 Vdc (also to ground)
- Max permissible DC voltage Um: 1800 Vdc (also to ground)
- Normal Max. operating temperature: 90°C
- Min. operating temperature: -40°C
- Max. overload temperature: 120°C
- Max. short circuit temperature: 250°C

Special features

- The cable shall be tested to work for at least 25 years (EN 50618)
- Thermal endurance properties: 20 000 h a max. conductor temperature of 120°C at a max. ambient temperature of 90°C (EN 60216)

The most typical cross sections for these cables are 4, 6 and 10 mm^2, depending on the maximum allowed voltage drop and power losses.

In case a cross section is required for Array cables which is not available on the market, use of more common Cu or Al/PVC/XLPE cables is also permitted, provided that:

- These are not directly exposed to the sun (e.g. laid in conduit or trunking);

- Cables withstand voltage compatible with the maximum voltage of the Solar PV System are chosen. The rule to apply is that a cable with U0/U kV AC voltage is able to withstand a DC voltage up to 1.5 times U0. Therefore, for instance, a U0/U 0.6/1kV cable can be used in a Solar PV system whose voltage does not exceed 1.5 x 600 = 900 Vdc.

8.2.2.2 AC side cables

With regard to the cables on the AC side of the Solar PV System, that is downstream the inverter, the same considerations made for AC installations as per Saudi Building Code apply. Obviously, cables with U/U0 = 0.6/1kV can in this case be used for AC systems with voltage to earth up to 600 Vac.

8.2.2.3 Selection of cable cross section

The cross-sectional area of a cable shall be chosen such as that:

- its current carrying capacity Iz is not lower than the design current Ib
- the voltage drop at its end is within the fixed limits.

Cable cross section selection according to current carrying capacity

Under normal service conditions, each module supplies a current near to its characteristic short-circuit value, so that the service current for the string circuit is assumed to be equal to:

$$Ib = 1.35 \times I_{SC\_MOD}$$

where I_{SC_MOD} is the short-circuit current of the PV module under standard test conditions and the 35% rise accounts for radiation values higher than $1kW/m^2$.

When the PV System is divided into sub-arrays, the PV sub-array cables shall carry a design current equal to:

$$Ib = N_{SA} \times 1.35 \times I_{SC\_MOD}$$

where N_{SA} is the number of strings which form the sub-array relating to the same PV string combiner box (see for example Figure 24, where the represented PV Array can be confused with a Sub-Array).

The current carrying capacity Iz0 of the cables is usually declared by the manufacturers at either 20 or 30°C in free air. To take into account also the methods of installation and the temperature conditions, the current carrying capacity Iz0 shall be reduced by a correction factor as obtained from the product of:

- Derating factor due to the proximity of cables to the modules (k1) (by assuming a temperature of 80°C). In case the cable laying is inside conduits or trunkings, this derating factor can be further reduced of a 10%, unless the current carrying capacity of the cable is already declared for this laying condition by the manufacturer
- Derating factor due to proximity with other cables when laid in conduits or trunking (k2). Values indicated by the cable manufacturers shall be adopted in this case

When not declared by the manufacturer, these values can be taken equal to:

	Iz0 declared at 20°C	**Iz0 declared at 30°C**
k1	0.38 (0.34 if laying into conduits or trunking is also considered)	0.41 (0.37 if laying into conduits or trunking is also considered)
k2	0.8 (2 circuits)	0.8 (2 circuits)

	0.7 (3 circuits) 0.65 (4 circuits)	0.7 (3 circuits) 0.65 (4 circuits)

In case the cables are not placed near the back side of the PV modules, for example in the connection between the string combiner box to the inverter, and when the derating factor is not declared by the manufacturer, the above mentioned derating factors can be assumed equal to:

	For laying of cables far from the PV modules (50°C)
	Iz0 declared at 30°C
k1	0.816 (0.73 if laying into conduits or trunking is also considered)
k2	0.8 (2 circuits) 0.7 (3 circuits) 0.65 (4 circuits)

if a temperature up to 50°C is considered at the laying conditions of the cable.
Therefore, the following condition will have to be fulfilled for the selected string cable:

$$I_z = I_{z0} \times k1 \times k2 \geq 1.35 \times I_{SC\_MOD}$$

Whereas for a Sub-Array cable, the following will hold:

$$I_z = I_{z0} \times k1 \times k2 \geq N_{SA} \times 1.35 \times I_{SC\_MOD}$$

Other recommendations given by the cable manufacturers will also be taken into account.

Cable cross section selection according to voltage drop

Let alone the voltage drop considerations and calculation on AC lines, which are as conventionally known, some concepts are here presented for the verification of the voltage drop along a DC line, which can be of less common use for Consultants and Contractors.
In fact, in addition to the choice of the cross-sectional area of a cable related to the current to be carried, the voltage drop is also a criterion to be checked for the definition of a cable cross section, as the limitation of this drop means a limitation of the power losses. In fact, it should be borne in mind that a DC line is only resistive, therefore the voltage drop and the loss of power along a DC line have strictly related one another.
The voltage drop for a DC line, namely for the line which connects a Solar PV string with the string combiner box, rather than directly to the inverter, can be calculated by means of proper tables which are provided by the cable manufacturers.
An example of a table of this type is given in Figure 29. The voltage drop for a Two core cable DC can be calculated by means of the following formula:

$$\Delta V\% = \left(\Delta V_{mV/m/A}(S_1) \times L_{comb.box-string} + \Delta V_{mV/m/A}(S_{\text{mod}}) \times \frac{L_{\text{mod}}}{2} \right) \times \frac{P_{\max string}}{1000 \times V^2} \times 100$$

where:

$\Delta V_{mV/m/A}$ = voltage drop per Ampère per meter as taken from a table like that in Figure 29
$P_{max\ string}$ / V = current in the string under verification
$L_{comb.box\text{-}string}$ = is the length of the path between the combiner box (or from the inverter) and the string of modules of the cable under verification
S = is the cross-section of the cable under verification
L_{mod} = is the length of the cables already connected to the modules, summed up to compose the string. Usually, the PV Modules have two cable leads each one having a length of 1m. The total length to be considered would be in this case 2 leads × 1m × $N_{modules\ /\ string}$ m

VOLTAGE DROP PER AMPERE PER METER (mV). Conductor operating temperature: 70ºC

Conductor Cross Sectional Area	Two Core Cable D.C.	Two Core Cable Single Phase A.C.	Three or Four Core Cable Three phase A.C.
mm	mV	mV	mV
1.5	29	29	25
2.5	18	18	15
4	11	11	9.05
6	7.3	7.3	6.04
10	4.4	4.4	3.08
16	2.8	2.8	2.04

Figure 29 – Voltage drop calculation table

In case no tables are available, or a calculation spreadsheet is to be prepared to automatize the checks, the following procedure can apply:

1) The resistivity of the copper cable is figured out at the maximum operating temperature of the cable, i.e. 90°C as mentioned in 8.2.2.1:

$$\rho_{90^\circ C} = \rho_{20^\circ C} \times (1 + \alpha \times \Delta T) = 0.018 \times \left[1 + 4 \cdot 10^{-3} \times (90 - 20)\right] \cong 0.023 \frac{\Omega \cdot mm^2}{m}$$

2) The maximum power of the string is obtained from:

$$P_{max\ string} = N_{modules\ /\ string} \times P_{mod}$$

where, $N_{modules\ /\ string}$ = number of modules which compose the string
P_{mod} = rated power of each single module

3) The operating voltage of the string is obtained as:

$$V = N_{modules\ /\ string} \times V_{MPP}$$

where, V_{MPP} = voltage at maximum power of each single module
Assuming that:
$L_{comb.box\text{-}string}$ = is the length of the path between the combiner box (or from the inverter) and the string of modules of the cable under verification
S = is the cross-section of the cable under verification

L_{mod} = is the overall length of the cables already connected to the modules, summed up to compose the string. Usually, the PV Modules have two cable leads each one having a length of 1m. The total length to be considered would be in this case 2 leads × 1m × $N_{modules / string}$ m

S_{mod} = is the cross-section of the module cable (normally 4mm^2)

The voltage drop along the string cable under consideration can be calculated as:

$$\Delta V\% = \rho_{90°C} \times \left[\left(\frac{2 \times L_{comb.box-string}}{S_1} + \frac{L_{mod}}{S_{mod}} \right) \right] \times \frac{P_{max\,string}}{V^2} \times 100$$

Similar considerations and evaluation as made for string cables can be carried out to calculate the voltage drop of the PV array cable which can be connected between the combiner box and the inverter. The values of the voltage drops will be summed up and it is recommended that the overall voltage drop not to exceed 1-2% as calculated for the longest string in the Solar PV Array from the inverter.

Cables from the combiner boxes to a DC panel are not in touch with the modules, therefore these are placed in an environmental temperature which is usually not higher than 50°C. There is no need then to use cables with the above strict characteristics, provided they are anyway protected against solar radiation. If the cables follow a path outside, this is achieved by laying the cables in conduits or trunkings which are suitable for outdoor use. Conversely, if these are laid inside the buildings, the rules which usually apply to electrical installations are valid.

8.3 Safety of the PV array

8.3.1 Maximum DC voltage

In case the maximum PV array voltage, as calculated at the minimum outdoor temperature of 0°C, exceeds 1000 Vdc, the entire PV array and associated wiring and protection, shall have access restricted to competent persons only. PV arrays for installation on buildings shall not have maximum voltages greater than 1000 Vdc.

For protection against electric shock, the requirements of IEC 60364-4-41 shall apply. PV module exposed metal earthing and bonding shall be according to applicable standards.

8.3.2 Protection against overcurrent in the DC section

Overcurrent within a PV array can result from earth faults in array wiring or from fault currents due to short circuits in modules, in junction boxes, PV array combiner boxes or in module wiring.

In a PV array formed by a number of strings, fault conditions can give rise to fault currents flowing through parts of the DC system. Two key problems need addressing, that is overloaded string cables and excessive module reverse currents, both of which can present a considerable fire risk.

PV modules are current limited sources, but they can be subjected to overcurrent because they can be connected in parallel and also connected to external sources. The overcurrent can be caused by the sum of currents from PV strings, PV sub-arrays and PV arrays with direct functional earth connection.

8.3.2.1 Solar PV cables overcurrent protection

From the point of view of protection against overloads, this can be omitted:

- for PV DC string cables, if they are chosen with a current carrying capacity $Iz \geq 1.35 \times I_{SC\_MOD}$
- for PV DC sub-array cables, if they are chosen with a current carrying capacity $Iz \geq 1.35 \times I_{SC\ S\text{-}ARRAY}$ where $I_{SC\ S\text{-}ARRAY} = N_{SA} \times I_{SC\_MOD}$
- for PV DC array cables, if they are chosen with a current carrying capacity $Iz \geq 1.35 \times I_{SC\ ARRAY}$, where $I_{SC\ ARRAY} = N_S \times I_{SC\_MOD}$

This rule is similar to what stated in clause 712:43-3 on Section 401 of the Saudi Building Code, but with the coefficient 1.25 modified into 1.35 to account for the specific climatic condition in KSA, where heightened irradiance and a routinely exceeding of the STC of PV modules is likely to happen.

As regards short-circuits, the cables on the DC side are affected by such overcurrent in case of:

- fault between the two poles of the PV system;
- fault to earth in the earthed systems;
- double fault to earth in the earth-insulated systems.

These rules apply in this case for the protection against overcurrent of PV string cables:

1) in case one or two strings ($N_S = 1$, $N_S = 2$) are directly connected to an inverter, the overcurrent protection for each string can be omitted, provided the PV string cable has been rated with the above rule $Iz > Ib = 1.35 \times I_{SC\_MOD}$;
2) in case three or more strings ($N_S \geq 3$) are directly connected to an inverter (same MPPT input), the overcurrent protection shall be necessary for each string whenever the current carrying capacity of the string cable is:

$$I_Z < (N_S - 1) \times 1.35 \times I_{SC\_MOD}.$$

Conversely, it can be omitted, but the need to protect the modules against overcurrent has to be evaluated in this case (see upcoming paragraphs).

In case of a fault in a PV sub-array cable, the overcurrent protection shall be necessary on this cable whenever its current carrying capacity is lower than the maximum contribution to the short circuit given by the remaining sub-arrays, that is:

$$I_Z < (N_S - N_{SA}) \times 1.35\ I_{SC\_MOD}$$

In case of a fault in a PV array cable, the overcurrent protection shall be necessary on this cable whenever its current carrying capacity is lower than the maximum contribution to the short circuit given by the whole array, that is:

$$I_Z < N_S \times 1.35 \times I_{SC\_MOD}$$

For the choice of the rating current of the overcurrent protection for string and sub-array / array refer to 8.3.2.2 and 8.3.2.3 respectively.

In fact, while string cable sizes can be increased as the number of parallel connected strings (and the potential fault current) increases, and therefore the cables can result to be protected by a correct choice of the cross section, the ability of a module to withstand the reverse current must also be considered. This normally requires the provision of a proper device (fuse, circuit breaker), as explained in 8.3.2.2

8.3.2.2 PV string overcurrent protection

Where currents exceed the modules maximum reverse current rating, there is the potential for damage to the affected modules and also a fire risk. IEC61730-2 Photovoltaic (PV) module safety qualification – Part 2: Requirements for testing, includes a reverse current overload test. This reverse current test is part of the process that enables the manufacturer to provide the maximum overcurrent protection rating or maximum series fuse ($I_{MOD\_MAX\_OCPR}$). Fault currents above the maximum series fuse rating present a safety risk and must be addressed within the system design.
Therefore, string overcurrent protection shall be mandatory if:

$$((N_S - 1) \times I_{SC\_MOD}) > I_{MOD\_MAX\_OCPR}$$

Where fuses are applied, these fuses need to meet the requirements as described in IEC 60269-6 (Type “gPV”)”.
Where string overcurrent protection is required, either (see Figure 30 and Figure 31):
a) Each PV string shall be protected with an overcurrent protection device (e.g. fuse or circuit breaker), where the nominal overcurrent protection rating of the string overcurrent protection device shall be I_n where:

$$I_n > 1.5 \times I_{SC\_MOD} \text{ and}$$
$$I_n < 2.4 \times I_{SC\_MOD} \text{ and}$$
$$I_n \leq I_{MOD\_MAX\_OCPR}$$

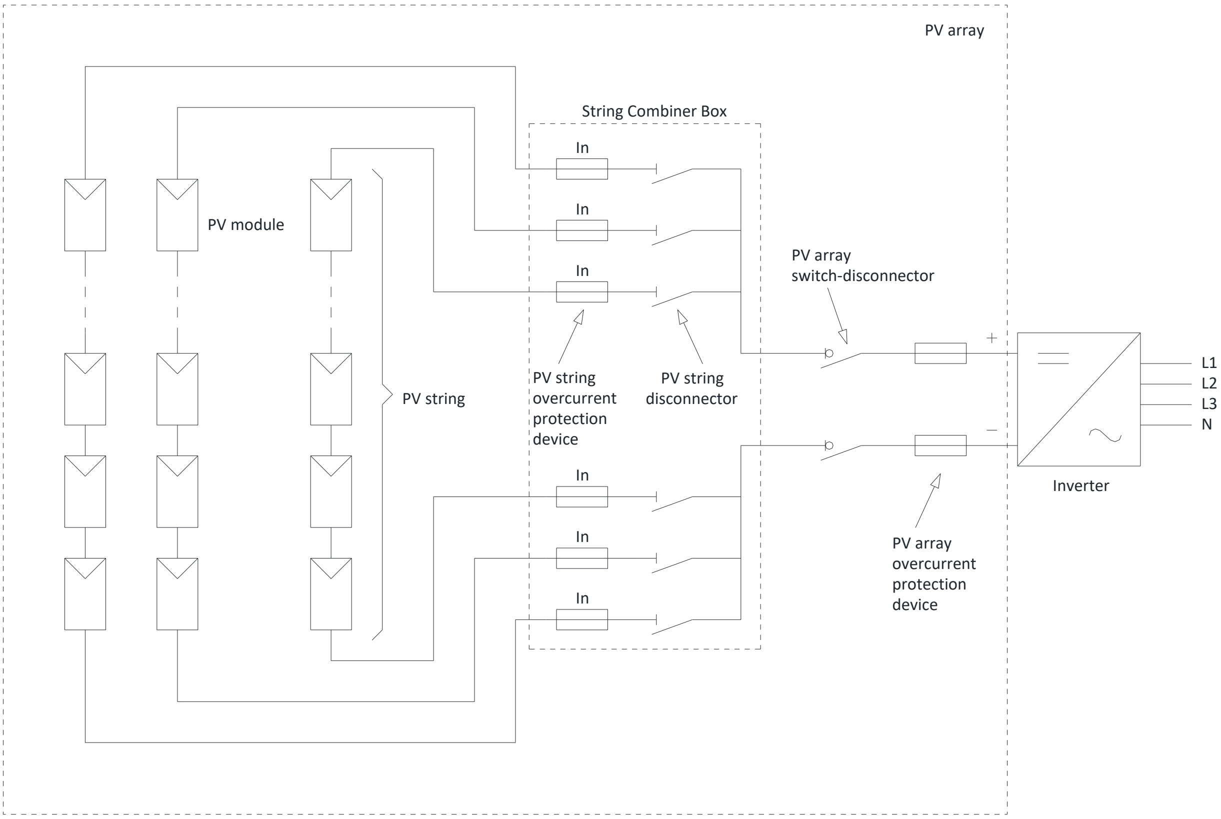


Figure 30 – Example of a PV array diagram with multiple parallel string – String overcurrent protection (source SASO IEC 62548)

or

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

$$I_{ng} > 1.5 \times N_G \times I_{SC\_MOD} \text{ and}$$
$$I_{ng} < I_{MOD\_MAX\_OCPR} - ((N_G - 1) \times I_{SC\_MOD})$$

Where:

- N_G is the number of strings in a group under the protection of one overcurrent device;
- I_{ng} is the nominal overcurrent protection rating of the group overcurrent protection device.

In some PV module technologies I_{SC_MOD} is higher than the nominal rated value during the first weeks or months of operation. This should be taken into account when establishing overcurrent protection and cable ratings.

NOTE: Strings can generally only be grouped under one overcurrent protection device if $I_{MOD\_MAX\_OCPR}$ is greater than $4 \times I_{SC\_MOD}$.

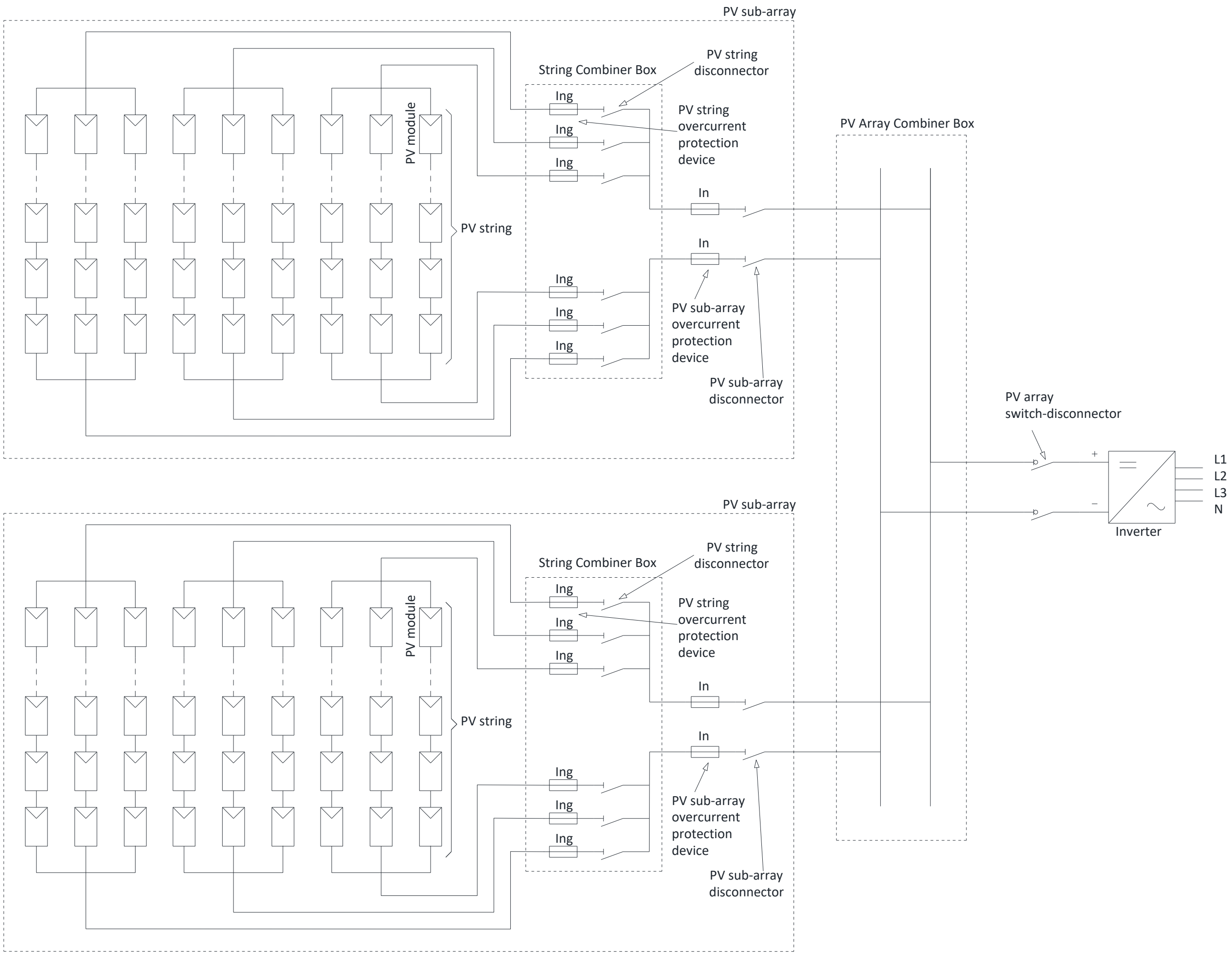


Figure 31 – Example of a PV array diagram where strings are grouped under one overcurrent protection device per group (source SASO IEC 62548)

8.3.2.3 PV sub-array and array overcurrent protection

The nominal rated current (I_n) of overcurrent protection devices for PV sub-arrays shall be determined with the following criteria:

$$I_n > 1.35 \times I_{SC\ S\text{-}ARRAY} \text{ and}$$
$$I_n \leq 2.4 \times I_{SC\ S\text{-}ARRAY}$$

The nominal rated current (I_n) of overcurrent protection devices for PV arrays shall be determined with the following criteria:

$$I_n > 1.35 \times I_{SC\ ARRAY} \text{ and}$$
$$I_n \leq 2.4 \times I_{SC\ ARRAY}$$

The 1.35 multiplier used here instead of the 1.5 multiplier used for strings is to allow designer flexibility but also taking into account of the heightened irradiance.

8.3.2.4 Coordination between cable cross section and overcurrent protective device

For the purpose of protecting 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:

$$(I_{sc}^2 \times t) \leq K^2 \times S^2$$

Where:

$(I_{sc}^2 \times t)$ 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 ($K=143\ As^{1/2}/mm^2$ for solar cables with insulation in EPR or XLPE);

S is the cross-sectional area of the cable (in mm^2).

As well known, this holds not only for cables at the DC side, but also for cables at the AC side. In that case, “I” will be the maximum current which can be drawn from the distribution system in case of fault.

8.3.2.5 Overcurrent protection location

In compliance with SASO IEC 62548, overcurrent protection devices, where required, shall be placed:

- for string overcurrent protection devices, they shall be placed 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 placed where the sub-array cables join the array cables in the array combiner box;
- for array overcurrent protection devices, they shall be placed where the array cables join the power conversion equipment.

Overcurrent protection devices shall be installed in readily available locations.

An overcurrent protective device required for a string cable or sub-array cable shall be placed in each live conductor (i.e. each live conductor not connected to the functional earth).

An exception applies for systems that are not functionally earthed (i.e. do not have any PV array DC live conductors connected to earth) and that have only two active conductors if:

- there is segregation by a physical barrier between string cables and sub-array cables, or
- there are no sub-arrays and therefore no sub-array cables i.e. in small systems,

In this case, an overcurrent protective device need only be placed in one unearthed live conductor of the string cable or sub-array cable. The polarity of this conductor shall be the same for all cables thus protected.

8.3.2.6 Blocking diodes

As stated in SASO IEC 62548, blocking diodes may be used to prevent reverse currents in sections of a PV array. These are normally due to inevitable mismatches between the PV modules characteristics, despite the rules as set in 8.1.3 have to be observed. However, blocking diodes shall not be used as an alternative to overcurrent protective devices.

If used, blocking diodes shall comply with the following requirements:

- have a voltage rating at least 2 times $V_{oc\ max}$;

- have a current rating I_{MAX} of at least 1.4 times the short circuit current at STC of the circuit that they are intended to protect; which can be calculated as follow:

$$1.4 \times I_{SC\_MOD} \text{ for PV strings;}$$
$$1.4 \times I_{SC\ S\text{-}ARRAY} \text{ for PV sub-arrays;}$$
$$1.4 \times I_{SC\ ARRAY} \text{ for PV arrays;}$$

- be installed so no live parts are exposed;
- be protected from degradation due to environmental factors.

8.3.3 Protection against overcurrent in the AC section

Protection against overcurrent of the Solar PV System AC connection cables and inverters can be based on the following criteria:

1) Protection against overload: the current carrying capacity of the AC supply cables and the rated current for the overload protective device shall take into account the design current of the inverter. This is the maximum AC current given by the inverter manufacturer or, failing that, 1.1 times its rated AC current can be assumed. To be noted that, since the cable connecting the inverter to the point of parallel with the distribution network is usually dimensioned to obtain a current carrying capacity higher than the maximum current which the inverter can deliver, a protection against overload would not be needed;
2) Protection against overcurrent (short-circuit): the Solar PV System AC supply cable and the inverter shall be protected from the effects of short-circuit by an overcurrent protective device installed at the connection to the designated distribution board of the electrical installation (in accordance with both 712:43-4 on Section 401 of the Saudi Building Code and IEC 60364). The maximum short circuit current to be considered in this case is only the current coming only from the distribution network.

The installation of a LV circuit-breaker requires that its short-circuit breaking capacity (or that of the CB together with an associated device) be equal to or exceeds the calculated prospective short-circuit current at its point of installation.
The installation of a circuit-breaker in an LV installation must fulfil one of the two following conditions:

- Either have a rated short-circuit breaking capacity Icu (or Icn) which is equal to or exceeds the prospective short-circuit current calculated for its point of installation, or
- If this is not the case, be associated with another device which is located upstream, and which has the required short-circuit breaking capacity

In the second case, the characteristics of the two devices must be co-ordinated such that the energy permitted to pass through the upstream device must not exceed that which the downstream device and all associated cables, wires and other components can withstand, without being damaged in any way. This technique is profitably employed in:

- Associations of fuses and circuit-breakers
- Associations of current-limiting circuit-breakers and standard circuit-breakers.

This is known as “cascading” (or backup) of circuit breakers and it shall be carefully addressed with the help of co-ordination tables given by the manufacturers.

To protect the cable, the main circuit-breaker of the consumer plant can be used if the specific let-through energy can be withstood by the cable. However, the trip of the main circuit-breaker will put all the Eligible consumer installation out of service.
In multi-inverter plants, the presence of one protection for each 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.

8.3.4 Isolation and Switching

Disconnecting means shall be provided in PV arrays according to Table 6 in SASO IEC 62548 (and illustrated in figures below) to isolate the PV array from the inverter and vice versa and to allow for maintenance and inspection tasks to be carried out safely. Overcurrent protection shall also be provided, when required according to the criteria illustrated in 8.3.2 and 8.3.3.
The disconnecting means for inverters shall be accessible and meet the requirements of a switch-disconnector as per SASO IEC 62548.
Some of the most recurrent cases are shown in the following, by pointing out which disconnecting means are either mandatory or recommended. Reference to SASO IEC 62548 shall be made for any other cases not covered here.

WARNING

As a general recommendation for disconnecting means at the DC side, it is worth noting that, although permitted by international Standards, though with some specific conditions, it is not recommended to rely on plugs /sockets and connectors as isolating means. In fact, these are normally not constructed for load interruption. Disconnection of these under load represents a safety risk, which incurs damage to the connection with also risk of fire.

1) One (or two) string(s) directly connected to an inverter (one string which coincides with a PV array): the disconnection means to envisage are at least the following (see Figure 32):

- a switch-disconnector (i.e. having under load switching capacity), typically already built into the inverter, sufficient to guarantee isolation of the DC circuit;
- a circuit breaker (or also a switch disconnector with fuses) on the AC side is required to protect the AC line from Main AC Panel to the inverter (8.3.3). This provides also a means of isolation;
- an additional switch-disconnector at the AC side of the inverter and installed in a panel in the vicinity of this latter, can be advisable in case the inverter is installed far from the Main AC Panel.

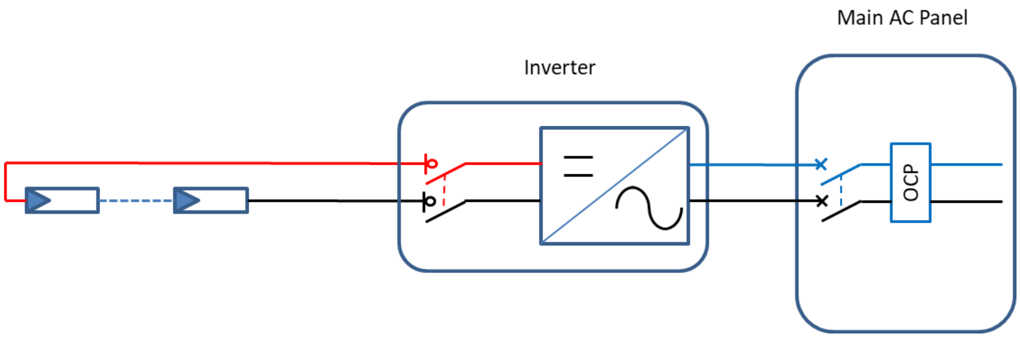
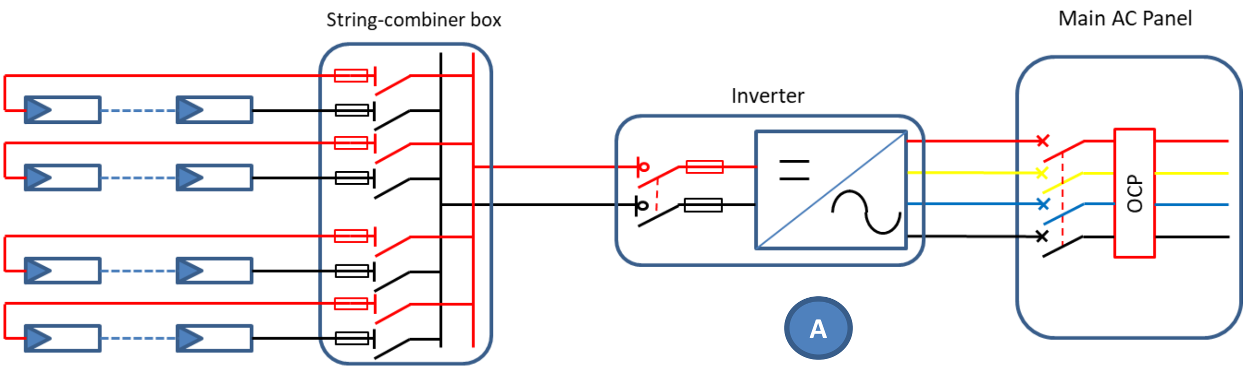


Figure 32 – Disconnection means – One string directly connected to an inverter

2) More than two strings connected either to a string combiner box or directly to an inverter: the disconnection means to envisage are at least the following (see Figure 33):

– a disconnector for each string in the string combiner box, recommended but not mandatory, with overcurrent protection (e.g. fuse) if required (refer to 8.3.2). For the case represented, the need of an overcurrent protection is very likely to be needed due to the number of strings connected to the combiner box;
– a main array switch-disconnector (i.e. having under load switching capacity), typically already built into the inverter, sufficient to guarantee isolation of the whole DC PV array;
– a circuit breaker (or also a switch disconnector with fuses) on the AC side is required to protect the AC line from Main AC Panel to the inverter (refer to 8.3.3). This provides also a means of isolation;
– an additional switch-disconnector at the AC side of the inverter and installed in a panel in the vicinity of this latter, can be advisable in case the inverter is installed far from the Main AC Panel.



The string combiner box is not mandatory and it can be omitted, provided the inverter has sufficient inputs to connect all the PV Strings. In this case, direct connection of the string to the inverter is possible, where no isolation of each single string is provided and overcurrent protection of each single string is normally achieved via an electronic device, permitted by the construction and safety standards. This situation is depicted in Figure 33 (B) and similar considerations as per Figure 33 (A) can be repeated.

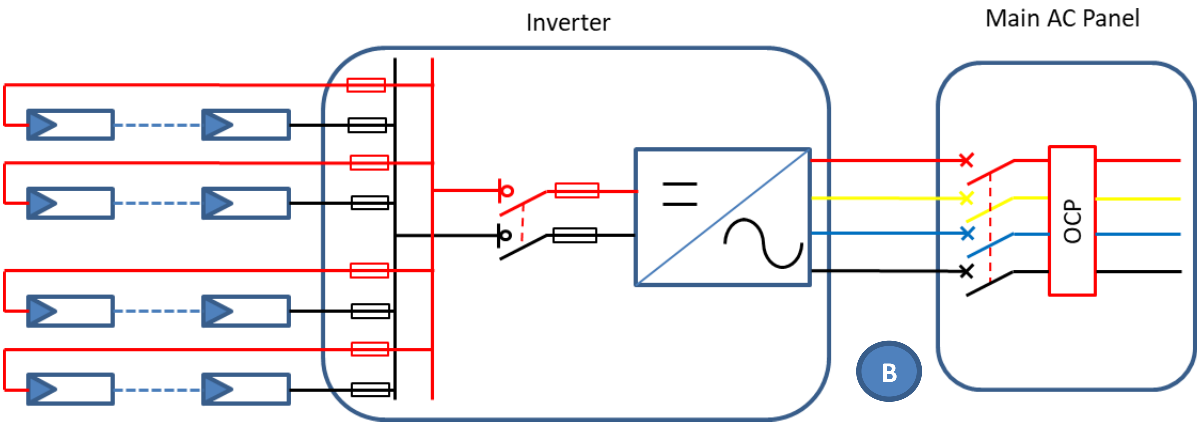


Figure 33 – Disconnection means – More than two strings connected either to a string combiner box (A) or directly connected to an inverter (B)

3) More than two strings connected to string combiner boxes and grouping in two sub-arrays: the disconnection means to envisage are at least the following (see Figure 34):

– a disconnector for each string in the string combiner box, recommended but not mandatory, with overcurrent protection (e.g. fuse) if required (refer to 8.3.2). For the case represented, the need of an overcurrent protection is very likely to be needed;
– a main array switch-disconnector (i.e. having under load switching capacity), either already built into the inverter or installed in a specific panel, sufficient to guarantee isolation of the whole DC PV array;
– a circuit breaker (or also a switch disconnector with fuses) on the AC side is required to protect the AC line from Main AC Panel to the inverter (refer to 8.3.3). This provides also a means of isolation;
– an additional switch-disconnector at the AC side of the inverter and installed in a panel in the vicinity of this latter, can be advisable in case the inverter is installed far from the Main AC Panel.

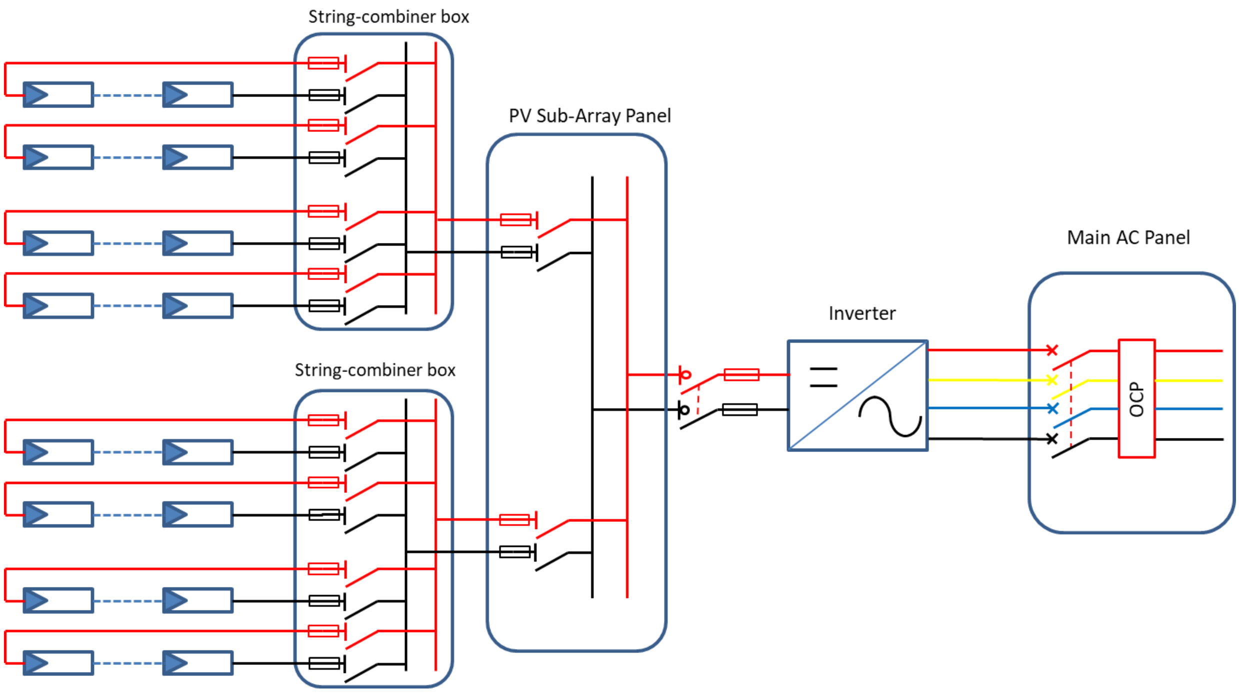


Figure 34 – Disconnection means – More than two strings grouped into two sub-arrays

A picture of a DC switch- disconnector built into an inverter is provided in Figure 35 - A), whereas in Figure 35 - B) a DC switch- disconnector to be used in a DC switchboard is shown.

Disconnection devices not capable of breaking load current should be marked as no-load break and should not be generally accessible.

An additional DC switch-disconnector may be specified for systems with long DC cable runs through buildings. This switch is generally used at the point of cable entry into the building.

A) *B)*

Figure 35 – Disconnection means – Example of DC disconnector switch: A) built into the inverter; B) on a separate DC panel

8.3.5 Earthing and bonding

The relation of a PV array to earth is determined by whether any earthing of the array for functional reasons is in use, the impedance of that connection and also by the earth status of the application circuit (e.g. inverter or other equipment) to which it is connected. Also the location of the earth connection with the previous mentioned parameters, all affect safety of the PV array.

The requirements of manufacturers of PV modules and manufacturers of the inverter to which the PV array is connected shall be taken into account in determining the most appropriate system earthing arrangement.

Protective earthing of any of the conductors of the PV array is not permitted. Earthing of one of the conductors of the PV array for functional reasons is allowed only if there is at least simple separation between PV array DC power circuits and main AC power output circuits provided either internally in the inverter or externally via a separate transformer (in the following, the term Separate Inverter will also be used, as suggested by SASO IEC 62548, to refer to an inverter with these characteristics).

A connection of one conductor to earth through internal connections inherent in the inverter via the neutral conductor is allowed in a system without at least simple separation.

The concept of earthing applied to a Solar PV System may involve both the exposed conductive parts (e.g. metal frame of the panels) as well as the generation power system (live parts of the PV system e.g. the cells).

In fact, the following options for earthing or bonding of parts of a PV array exist:

- Functional earthing of conductive non-current carrying parts (e.g. to allow for better detection of leakage paths to earth). In fact, it is worth noting that normally PV modules have a double or reinforced insulation (Class II ⧈), therefore earthing of frames would not be mandatory. However, for a correct working of RCM (Residual Current Monitoring) devices (see 8.3.6.3) this bonding is necessary. In a Solar PV System, although the choice of the equipment makes it apparently safer for the people to touch a live part, 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 increases 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 insulation means, 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.

Earthing of exposed conductive parts of a PV array shall be performed in accordance with the requirements of the flowchart shown in Figure 36.

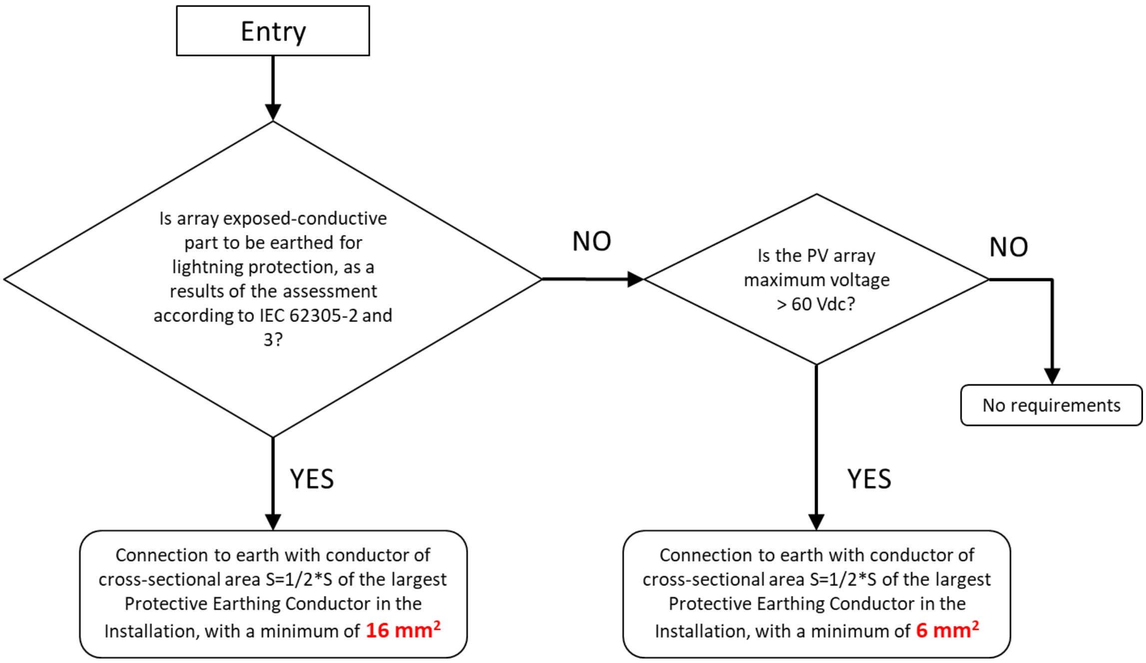


Figure 36 – PV Array exposed and extraneous conductive parts functional Potential Earthing and Equipotential Bonding – Decision tree (taken from SASO IEC 62548)

- Earthing for lightning protection.
- Equipotential bonding to avoid uneven potentials across an installation. PV module frames are to be considered extraneous-conductive parts only if the resistance measured between them and the main earthing terminal of the building (to which both exposed and extraneous-conductive parts are connected) is smaller than values specified by in force standards. In this case, equipotential bonding is needed, where the same rules as set in Figure 36 apply for the choice of the cross-sectional area of bonding conductors.
- Functional earthing of one current carrying pole of the PV array, so called functionally earthed PV array. In other words, some module types require earthing of one pole for proper operation and to avoid degradation. This earthing is considered to be functional earthing only. To be noted that a pole of a Solar PV System can be earthed only if it is galvanically separated (e.g. by means of a transformer) from the electrical AC network to which it is connected.

An earth conductor may perform one or more of these functions in an installation. The dimensions and location of the conductor are very dependent on its function, as visible in Figure 36.

If a separate earth electrode is provided for the PV array, this electrode shall be connected to the main earthing terminal of the electrical installation by main equipotential bonding conductors.

8.3.6 Protection against insulation faults

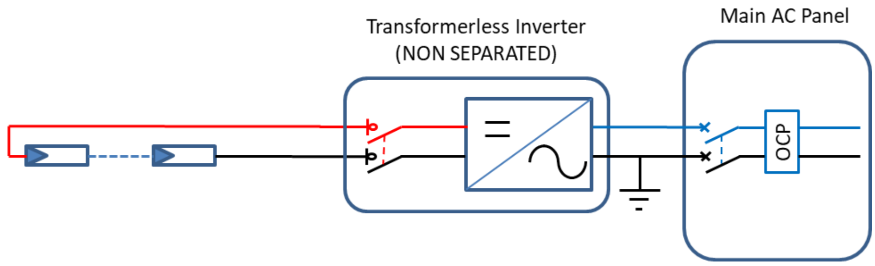
After having introduced the concepts of earthing and bonding for a Solar PV System in the previous paragraph, the way to detect first and to protect the system against insulation faults and people from indirect contacts is presented hereinafter.

8.3.6.1 Earth fault array detection (DC side)

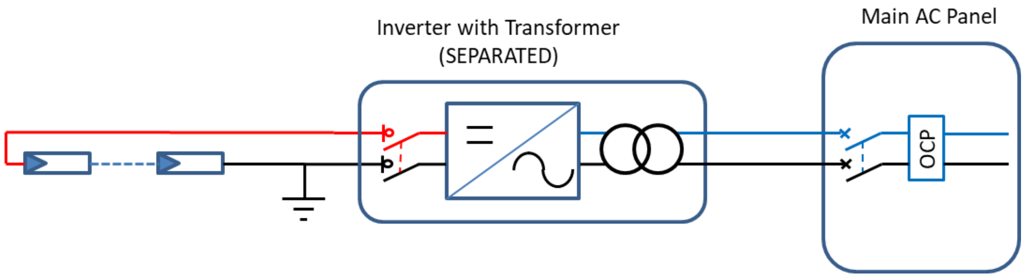
Requirements for detection of earth faults, actions required and alarms depend on the type of system earthing and whether the inverter provides electrical separation of the PV array from the output circuit (e.g. the distribution network).

The following categories are defined by the SASO IEC 62548 Standard:

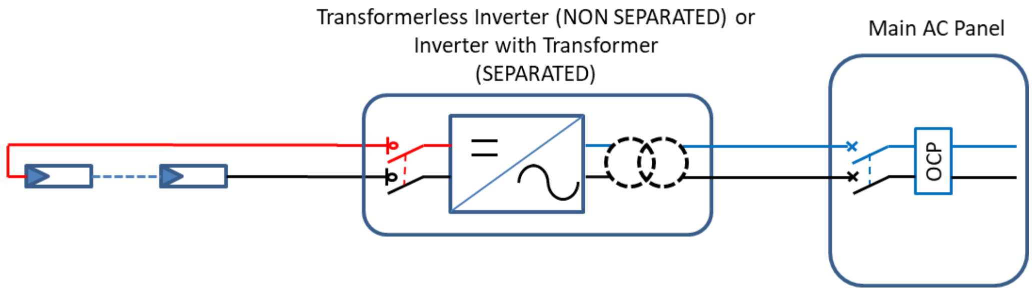
A) **Non separated PV arrays**, i.e. PV where PV DC circuits are connected to an earth referenced system through a non-separated (transformerless) inverter:



B) **Functionally earthed PV arrays**, i.e. an array with one of the main DC conductors connected to a functional earth (the inverter must be necessarily an inverter with transformer, as functional earthing of a DC pole is only allowed if there is a galvanic separation between the DC and AC circuits, through an inverter with transformer. Use of a transformerless inverter is allowed if an external AC/AC transformer is added). The functional earth bonding visible on the PV circuit in the figure below can also be included into the inverter:



C) **Non earth referenced PV arrays**, i.e. a PV array that has none of its main DC conductors referenced to earth either directly or through the inverter (this can be either transformerless or with transformer):



For PV systems whose DC voltage is higher than 120 V, Table 2 shows the requirements for measurements of PV array earth insulation resistance and PV array Residual Current Monitoring (RCM) as well as the actions and indications required if a fault is detected.

Table 2 – Requirements for different system types based on inverter isolation and PV array functional earthing

Table 2a - ***Monitoring of the insulation resistance***: the detection and response to abnormal values of insulation resistance is required to reduce hazards (i.e. risk of fire) due to degradation of insulation:

		System Type		
		Non separated PV arrays	**Functionally earthed PV arrays**	**Non earth referenced PV arrays**
Insulation resistance to earth of a PV array	**Measurement**	Through an insulation resistance monitoring or measurement device (see 8.3.6.2), which can also be provided within the inverter (a measurement is taken before starting operation and at least once every 24h)		
	Action on fault	Shutdown inverter and disconnect all conductors of the AC circuit or all poles of the PV array from the inverter OR Disconnect all poles of the faulty portion of the PV array from the inverter (operation of the inverter still possible and allowed in this case)	Shutdown inverter and disconnect all poles of the PV array from earth (1) OR Disconnect all poles of the faulty portion of the PV array from earth (operation of the inverter still possible and allowed in this case)	Connection to the AC circuit is allowed (the inverter is allowed to operate)
	Indication of fault	Necessary (usually included into the inverter; see 8.3.6.5). If the insulation resistance of the PV array to earth has recovered to a value higher than the limit shown in Table 3, the circuit is allowed to reconnect.		

(1) Through an opening device in the functional earthing, or by disconnecting all poles of the PV array or faulty portion of the PV array from the inverter, in case the functional earthing circuit is built into the inverter.

Table 2b – ***PV earth fault detection (at DC side) by means of Current Monitoring***: in case of reduction of the insulation resistance up to the circulation of a residual current, means are needed to act so as to clear the fault:

		System Type		
		Non separated PV arrays	**Functionally earthed PV arrays**	**Non earth referenced PV arrays**
PV earth fault detection by means of Residual Current Monitoring	**Detection / Protection**	Through a Residual Current Monitoring (RCM) system (see 8.3.6.3) which measures the total (both AC and DC components) RMS residual current and causes disconnection when this exceeds a given threshold	Through a Residual Current Monitoring (RCM) OR Through a device which is able to interrupt the PV array functional earth connection (see 8.3.6.4)	Not required
	Action on fault	Shutdown inverter and disconnect all conductors of the AC circuit or all poles of the PV array from the inverter OR Disconnect all poles of the faulty portion of the PV array from the inverter (operation of the inverter still possible and allowed in this case)	Disconnect all poles of the faulty portion of the PV array from the inverter OR Disconnection of the functional earth connection. Connection to the AC circuit and operation of the inverter still possible and allowed in this case	
	Indication of fault	Necessary (usually included into the inverter; see 8.3.6.5). If the insulation resistance of the PV array to earth has recovered to a value higher than the limit shown in Table 3, the circuit is allowed to reconnect.		

8.3.6.2 Array insulation resistance detection

These requirements, regarding detection and response to abnormal array insulation resistance to earth are intended to reduce hazards due to degradation of the insulation system.

A means shall be provided to measure the insulation resistance from the PV array to earth before starting operation and at least once every 24 h.

NOTE: This functionality for insulation resistance measurement may be provided within the inverter.

Minimum threshold values for detection shall be according to Table 3.

Table 3 – Minimum insulation resistance thresholds for detection of failure of insulation to earth

System size [kW]	R limit [kΩ]
≤ 20	30
>20 and ≤ 30	20
>30 and ≤ 50	15
>50 and ≤ 100	10
>100 and ≤ 200	7
>200 and ≤ 400	4
>400 and ≤ 500	2
> 500	1

It is recommended that the threshold of detection for insulation resistance should be set at values greater than the minimum values specified in Table 3. A higher value will increase the safety of the system by detecting potential faults earlier.

The measurement circuit shall be capable of detecting insulation resistance to earth of the PV array below the limit indicated above. It is necessary to remove the PV array functional earth connection during the measurement.

The action on fault required is dependent on the type of inverter in use, and shall be according to Table 2.

8.3.6.3 Protection by residual current monitoring system

Where required by Table 2, residual current monitoring (RCM) shall be provided that functions whenever the inverter is connected to an earth referenced output circuit with the automatic disconnection means closed. The residual current monitoring means shall measure the total (both AC and DC components) RMS residual current.

If the inverter AC output connects to a circuit that is isolated from earth, and the PV array is not functionally earthed, residual current monitoring is not required.

Detection shall be provided to monitor for excessive continuous residual current according to the limits shown below.

The RCM system shall cause disconnection within 0.3 s and indicate a fault if the continuous residual current exceeds:

- maximum 300 mA for inverters with continuous output power rating ≤ 30 kVA;
- the lesser of 5 A or (10 mA per kVA) of rated continuous output power for inverters with continuous output power rating > 30 kVA.

NOTE: It is possible to implement distributed residual current monitoring for example at sub-array level or in smaller subsections of the array. This can be beneficial especially in large arrays as it enables smaller thresholds of detection to be implemented. This can lead to more rapid identification of potential faults and can assist in identifying the section of the array that may be affected.

The RCM system may attempt to re-connect if the leakage threshold and the array insulation resistance meet the limits specified in Table 3.

8.3.6.4 Functionally earthed PV arrays – Interrupting means

Where required by Table 2b) and where residual current monitoring according to 8.3.6.3 is not provided, functionally earthed PV arrays shall be provided with a means of interrupting an earth fault which occur in the same PV array.
The device or association of devices shall automatically interrupt the current in the functional earthing conductor in the event of an earth fault on the DC side, and shall

- be rated for the maximum voltage of the PV array $V_{oc\ ARRAY}$

and

- have a rated breaking capacity not less than the maximum short circuit current of the PV array $I_{SC\ ARRAY}$ and
- have a rated current not exceeding that given in Table 4.

Table 4 – Nominal overcurrent rating of automatic functional earth fault interrupter

Total PV array power rating [kWp]	Rated current [A]
0 – 25	≤ 1
>25 – 50	≤ 2
>50 – 100	≤ 3
>100 – 250	≤ 4
>250	≤ 5

8.3.6.5 Earth fault indication and alarm

According to the indications provided in Table 2 an earth fault indication and alarm system shall be installed. If a fault in the system recovers, the indication may be reset automatically provided a record of the fault is maintained either by a log of faults or by an indication of previous faults. If a record of the fault is not able to be maintained, the original indication of a fault shall be maintained even if the fault (e.g. the insulation resistance) has recovered to an acceptable value.
The indication shall be of a form that ensures that the system operator or owner of the system becomes aware of the fault. For example, the indication system may be a visible or audible signal placed in an area where operational staff or system owners will be aware of the signal or another form of fault communication like RS485, e-mail, SMS or similar.
A set of operational instructions shall be provided to the system owner which explains the need for immediate action to investigate and to correct the fault.
Many inverters have earth fault detection and indication in the form of indicator lights. However, typical inverter mounting locations mean that this indication may not be noticed. SASO IEC 62109-2 requires that inverters have a local indication and also a means of signalling an earth fault remotely.

8.3.6.6 Residual Current Device (RCD) Protection at the AC side

Where an electrical installation includes a Solar PV System power supply that cannot prevent DC fault currents from entering the AC side of the installation, and where a Residual Current Device (RCD) is needed to satisfy the general requirements of the electrical installation in accordance with both Saudi Building Code (Section 401) and IEC 60364, then the selected RCD should be a Type B Residual Current Circuit Breaker (RCCB) as defined by SASO IEC 60755. This is to be installed in the circuit which connects the Main AC Panel of the installation with the inverter. The circuit breaker required in 8.3.3 and 8.3.4 can be the RCCB required if RCD is integrated into it, or a RCD can be installed beside this.

Where any doubt exists about the capability of the inverter to prevent DC fault currents entering the AC side of the system then the manufacturer shall be consulted.

In all the other cases, a Type A Residual Current Circuit Breaker (RCCB) shall be used if required by the Saudi Building Code (Section 401 – 41-3.1.4) and IEC 60364.

To avoid the RCD to be too sensitive, a size ≥ 300mA is recommended, or in any case with a current

$$Id \leq 50/R_E$$

Where R_E is the earthing resistance of the installation in case of TT Systems.

For TN Systems, reference to Saudi Building Code 41-3.1.3 can be made.

8.3.7 Protection of a Solar PV System against effects of lightning and overvoltage

8.3.7.1 General

A brief overview on lighting and overvoltage protection is given below. It is not the intention of this guidelines to cover all the aspects of this topic, therefore reference to proper applicable standards, particularly those of SASO IEC 62305 series, should be made.

As stated in SASO IEC 62548, the installation of a PV array on a building often has a negligible effect on the probability of direct lightning strikes; therefore, it does not necessarily imply that a lightning protection system should be installed if none is already present.

However, if the physical characteristics or prominence of the building do change significantly due to the installation of the PV array, it is recommended that the need for a lightning protection system be assessed in accordance with SASO IEC 62305-2 and, if required, it should be installed in compliance with SASO IEC 62305-3.

If a lightning protection system (LPS) is already installed on the building, the PV system should be integrated into the LPS as appropriate in accordance with SASO IEC 62305-3.

In the case where no lightning system is required on a building or in case of a free-standing ground mounted array, overvoltage protection may still be required to protect the array and the inverter and all parts of the installation.

8.3.7.2 Risk assessment for PV installations

The following method of risk assessment can be applied to evaluate if protection against transient overvoltage is required on the DC side. This is based on the evaluation of a critical length L_{crit} and its comparison with a length L, with the following meaning of these quantities:

• L is the maximum route length (m) between the inverter and the connection points of the PV modules of the different strings, or in other words the cumulative length of the DC lines. Therefore, L is the sum of:

- the sum of distances between the inverter(s) and the PV modules junction box(es), taking into account that the lengths of cable located in the same conduit are counted only once, and
- the sum of distances between the junction box and the connection points of the photovoltaic modules forming the string, taking into account that the lengths of cable located in the same conduit are counted only once.

- L_{crit} (m) depends on the type of PV installation, and is calculated according to Table 5 (taken from Table 712.1 of IEC 60364).

  SPDs shall be installed on the DC side of the installation if:

$$L \geq L_{crit}$$

Table 5 – Calculation of the critical length L_{crit}

	Type of installation	
	Solar PV Modules installation is attached to the building	**Ground Mounted Solar PV installation (i.e. not attached to the building)**
L_{crit}	115/Ng (14 m)	200/Ng (25 m)
$L \geq L_{crit}$	SPDs are required on the DC side	
$L < L_{crit}$	SPDs not mandatory on the DC side	

- Ng is the lightning ground flash density (flashes/km^2/year) relevant to the location to the power line and connected structures. Typical values in KSA depending on the area, can vary from 0.5 to 8 flashes/km^2/year. Therefore, the values of L_{crit} can be calculated accordingly as specified in Table 5. For the sake of safety, the highest number has been chosen to calculate L_{crit} in Table 5.

8.3.7.3 Protection against overvoltage

All DC cables should be installed so that positive and negative cables of the same string and the main array cable should be bundled together, avoiding the creation of loops in the system (see Figure 37). The requirement for bundling includes any associated earth/bonding conductors.

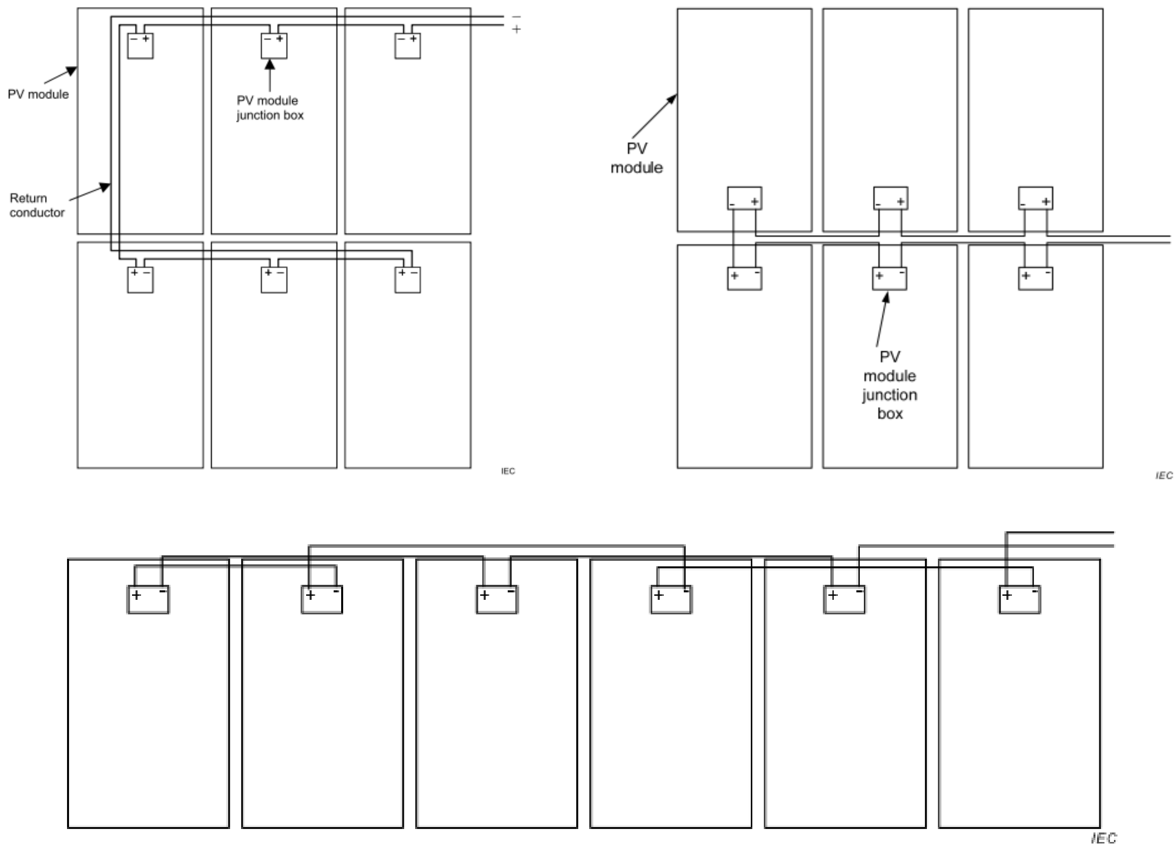


Figure 37 – Examples of wiring minimum loop area (source SASO IEC 62548)

Long cables (e.g. PV main DC cables over about 50 m) should be either

- installed in earthed metallic conduit or trunking, where the conduit or trunking is connected to the equipotential bonding;
- be buried in the ground (using appropriate mechanical protection);
- be cables incorporating mechanical protection which will provide a screen, where the screen is connected to the equipotential bonding, or
- be protected by a surge protective device (SPD).

These measures will act to both shield the cables from inductive surges and, by increasing inductance, attenuate surge transmission. Be aware of the need to allow any water or condensation that may accumulate in the conduit or trunking to escape through properly designed and installed vents.

8.3.7.4 Surge protection devices (SPDs)

To protect the DC system as a whole, surge protective devices (SPDs) can be fitted between active conductors and between active conductors and earth at the inverter end of the DC cabling and at the array.

SPDs are incorporated into electrical installations to limit transient overvoltages of atmospheric origin transmitted via the supply distribution system, whether AC or DC or both, and against switching surges. Some grid connected inverters have some form of in-built SPD; however discrete devices may also be required. In such cases, the coordination between the two SPDs should be verified with the equipment supplier.

To protect specific equipment, SPDs should be fitted as close as is practical to the equipment intended to be protected.
These measures are included here as a guide. Overvoltage protection is a complex issue and a full evaluation should be undertaken particularly in areas where lightning is common.
For the protection of the DC side, SPDs shall be compliant with EN 50539-11 and be explicitly rated for use on the DC side of a PV system. If the PV system is connected to other incoming networks (such as telecommunication and signalling services), SPDs will be required to protect the information technology equipment.
The following guidelines can then be given for the choice of the SPDs for Solar PV Systems and with reference to Figure 38:

Table 6 – SPD Position and Selection

SPD in Figure 38	Installation location	SPD Type	Criteria
1	In the inverter or in a specific panel at the DC side	Type 2	To be adopted if the risk assessment in 8.3.7.2 results in a need for DC SPDs (i.e. $L \geq L_{crit}$)
2	In the string combiner box, or in any case near the PV modules	Type 2	To be adopted if the distance between the PV modules and the inverter is > 10m
3	In the Main AC Panel	Type 1	-
4	In the inverter or in a specific panel at the AC side	Type 2	To be adopted if the distance between the inverter and the Main AC Panel is > 10m

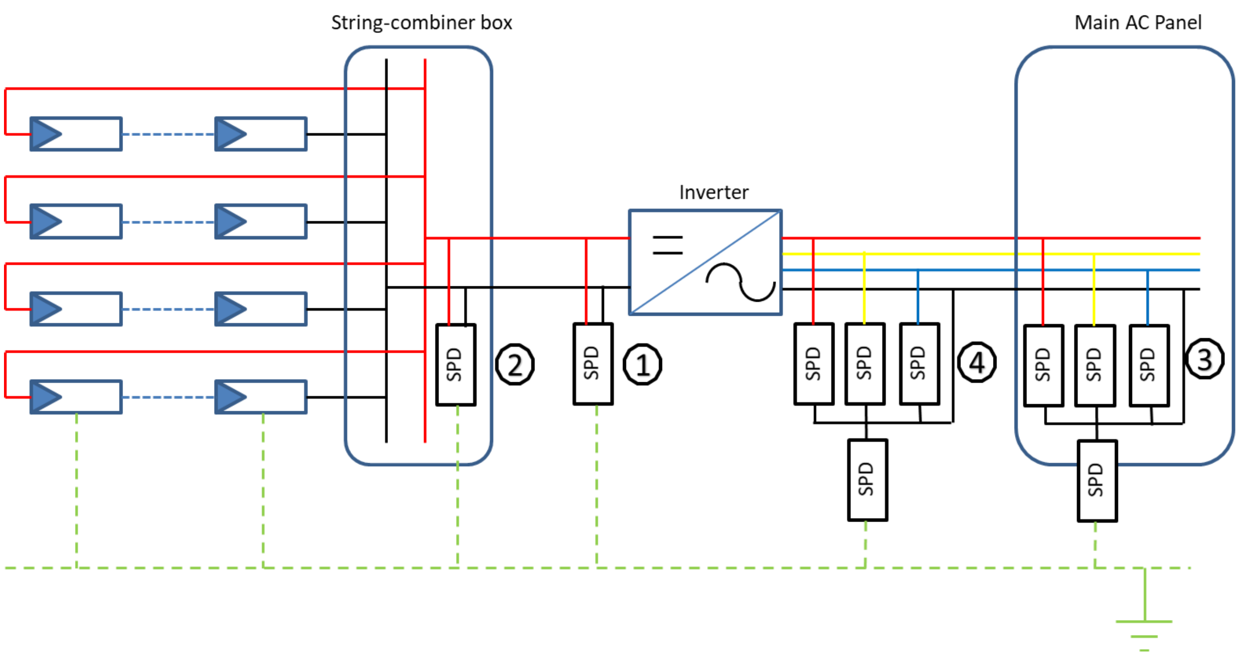


Figure 38 – Selection and position of SPDs

The minimum cross-sectional area of the cables for the connection of the SPDs both at DC and AC side is:

- $16mm^2$ for the connection of Type 1 SPDs to live conductors and to earth
- $4mm^2$ for the connection of Type 2 SPDs to live conductors and to earth

8.4 Safety of the Distribution Network

In case of a major fault in the distribution network, the Solar PV Systems do not have to contribute to worsen the condition. Therefore, it is required that they are provided with an Interface Protection, with the purpose to:

- disconnect the Small-Scale Solar PV System from the Distribution Network in the following cases
    - SEC de-energizes the Distribution Network (or the feeder) the Solar PV System is connected to;
    - the voltage and/or frequency values at the Exit point are out of the normal operating ranges;
- prevent the Small-Scale Solar PV System, when generating power, to cause over-voltages in the distribution network it is connected to.

It is not the purpose of the interface protection to:

- disconnect the Solar PV System from the Distribution Network in case of faults within the Eligible consumer’s installation;
- prevent damages to the Eligible consumer’s equipment (generating units or loads) due to faults/incidents (e.g. short circuits) in the Distribution Network or on the Eligible consumer’s installation; for such issues, the recommendations and requirements of the manufacturers of the equipment shall apply.

Details on the characteristics of the Interface Protection are given in the *Technical Standards for the Connection of Small-Scale Solar PV Systems to the LV and MV Distribution Networks of SEC*.

ANNEX A. EXAMPLE OF SIZING OF A SMALL-SCALE SOLAR PV SYSTEM

In this Annex an example of a Small-Scale Solar PV System to be connected to the SEC LV 230/400VAc Distribution Network of SEC is given.
It is the case of a household system, on a dwelling in Riyadh where an exploitable surface of about 20x8m is available on the roof.

Notice to the reader and disclaimer

The case presented in this Annex is only an example of sizing of Small-Scale Solar PV System and cannot be generalized for all possible cases, as the criteria which apply in the selection of the equipment can be various. The choices made with this case study are only for the sake of explanation and therefore not unique and not the only feasible. SEC disclaims liability for any personal injury, property or other damage, of any nature whatsoever, whether special, indirect, consequential, or compensatory, directly or indirectly resulting from the wrong application of the concepts here stated. Eligible consumers are responsible for observing or referring to the rules of good power engineering, to applicable laws and regulatory requirements.

Input data

The house is located in Riyadh, with the following data:

- Latitude: 24.68°N
- Longitude: 46.73°E
- Roof surface available: 160 m^2

The orientation of the house is S-E, with an azimuth angle of 7°, as visible in Figure 39.
It is assumed that, from a detailed site inspection, no objects that can cause shading to the PV modules have been detected.

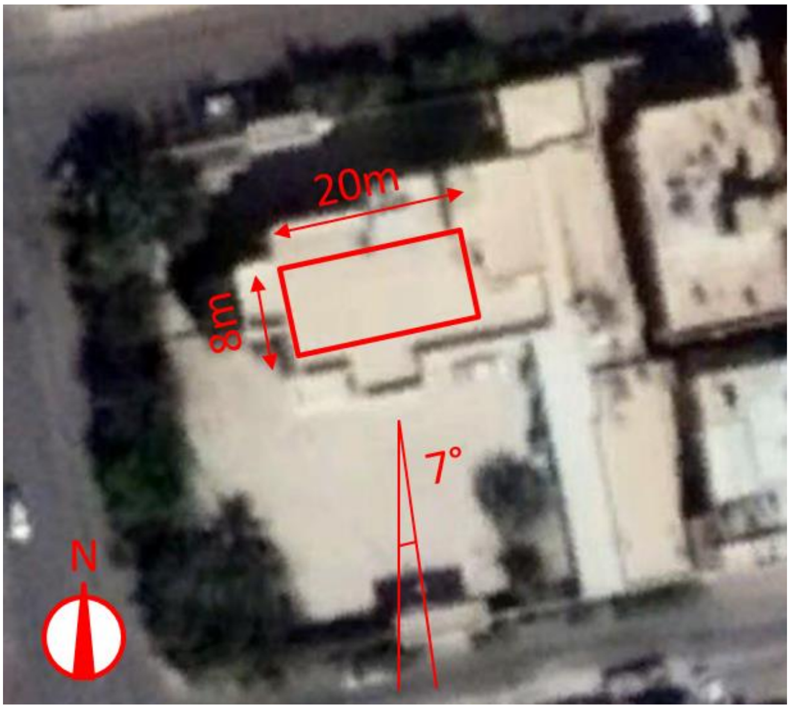


Figure 39 – Case Study of a Small-Scale Solar PV System for a residential dwelling in Riyadh

Yield energy

A first estimation of the energy that can be produced by a Small-Scale Solar PV System installed on the roof, can be obtained by retrieving the data from databases available on the web or with specific software, for the case under study by inputting the position and the azimuth angle.

The optimal inclination of the PV modules can also be evaluated.

For example, the tool PVGIS© European Union developed by the Joint Research Centre can be used to this purpose.

By introducing the longitude, latitude, azimuth angle data and by assuming a peak power of 1kWp as obtained from Crystalline silicon PV modules, an optimal tilt of 26° for the PV modules is suggested by PVGIS© :

PVGIS-5 estimates of solar electricity generation:

Provided inputs:

Latitude/Longitude:	24.678, 46.732
Horizon:	Calculated
Database used:	PVGIS-CMSAF
PV technology:	Crystalline silicon
PV installed:	1 kWp
System loss:	14 %

Simulation outputs

Slope angle:	26 (opt) °
Azimuth angle:	-7 °
Yearly PV energy production:	1830 kWh
Yearly in-plane irradiation:	2480 kWh/m²
Year to year variability:	26.10 %
Changes in output due to:	
Angle of incidence:	-2.5 %
Spectral effects:	-1 %
Temperature and low irradiance:	-10.9 %
Total loss:	-26.1 %

The following average values of monthly energy output are then obtained for the given system (per 1 kWp of PV module power installed):

Month	Average Monthly Produced Energy (kWh/kW/month)
January	145
February	151
March	164
April	143
May	151
June	147
July	152
August	158
September	160
October	168
November	145
December	146
TOTAL	**1830 (kWh/kW/year)**

The total actual energy produced by the Solar PV System will then be obtained once the size of this has been defined.

PV modules layout and maximum capacity of the PV System

While determining the size of a Solar PV System, it shall be borne in mind that:

- as required by ECRA Regulations [7], this cannot exceed the connected load for the consumption account;
- this is related to the available surface;
- the energy produced by the Solar PV Systems in a year should be compatible and comparable with the average energy consumption of the Eligible consumer, to avoid oversizing.

Many criteria can then drive the sizing of the PV System. In this case, with the purpose to illustrate a case study, the available surface will guide the definition of the maximum capacity, assuming that the other conditions are met.

To define the number of PV modules that can be installed in the available area on the roof, and then the size, evaluation of the shading between rows of PV modules has to be carried out to find out the spacing to be kept.

As the considerations made in 7.5 suggest, the condition to be evaluated is for the lowest sun path in the year, which happens at the winter solstice on December, 21st. In fact, the lowered sun height above the horizon will more likely produce shading. The sun paths can be recreated either by proper tools available on the web (Figure 40 shows a possible example) or by proper design software, specifically for the site, by inputting the latitude, longitude and the azimuth angle.

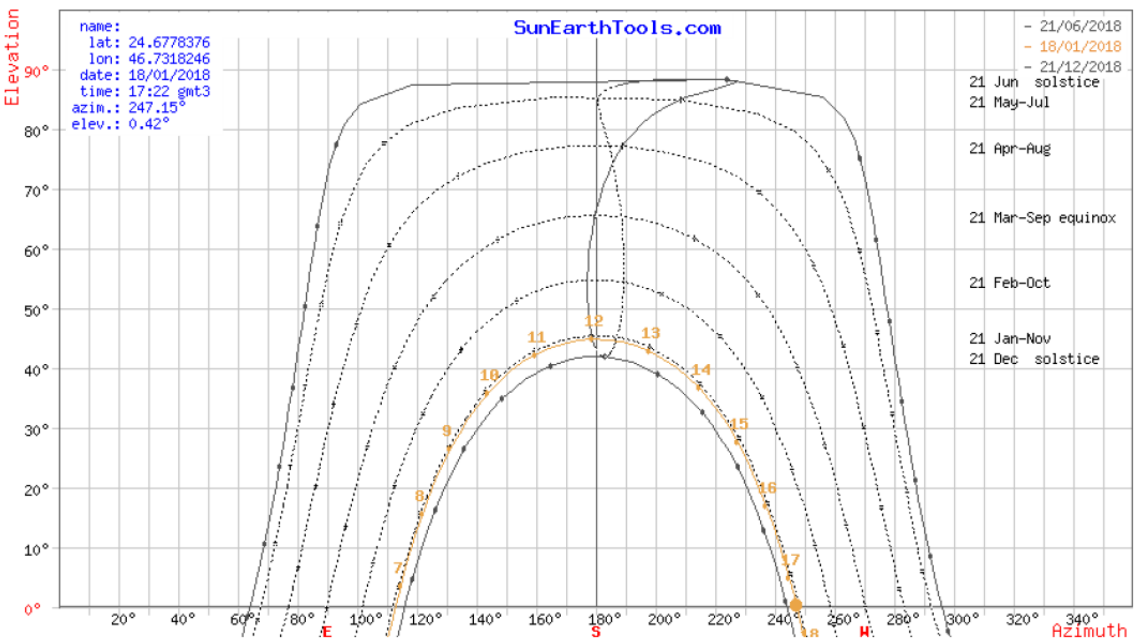


Figure 40 – Sun path for different days of the year, as visible from the site under study

Conventionally, one particular condition is considered to avoid shading, that is what happens at noon on December,21st. From Figure 40 a sun height of about 42° can be read in this condition.

This means that the situation to be evaluated to avoid shading between rows of PV modules is as shown in Figure 41.

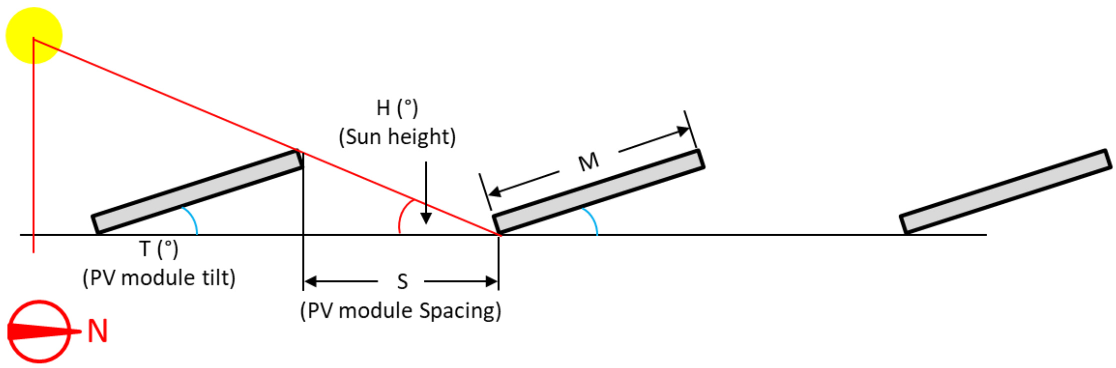


Figure 41 – Spacing between single PV modules or rows of PV modules

where:

- M is either the PV module width when the modules are in landscape format or the PV module length if they are in portrait format
- H(°) is the sun height at noon on December,21st , that is 42° as above discussed;
- T(°) is the tilt angle of the PV module, which has been set to 26° to optimise the yearly energy production;

It can be figured out that to avoid shading, the spacing S between either modules or rows of modules shall be such as:

$$S \times \tan(H(°)) \geq M \times \sin(T(°))$$

Assuming that modules with the following dimensions are used:

Module Dimensions	1650 x 992 mm
Cell orientation	60 Cells (10 x 6)

and that these are laid down in landscape format, the spacing between modules is:

$$S \geq \frac{M \times \sin(T(°))}{\tan(H(°))} = \frac{992 \times \sin(26°)}{\tan(42°)} = 483\text{mm}$$

A spacing of 0.5m can then be kept, and therefore the PV modules can be laid down as shown in Figure 42.

(In case the on-site survey has instead proved that other objects can cause shading, similar considerations apply and an evaluation like suggested in 7.5 can be undertaken)

This analysis based on the exploitation of the available roof surface, leads to the definition of a Solar PV System with 11 PV modules in 6 rows, for a total amount of 66, as visible in in Figure 42.

If use of Crystalline 300 Wp modules is made, this yields a Maximum Capacity of the PV System of:

$$P = N_{modules} \times P_{mod} = 66 \times 300 = 19800\ W_p$$

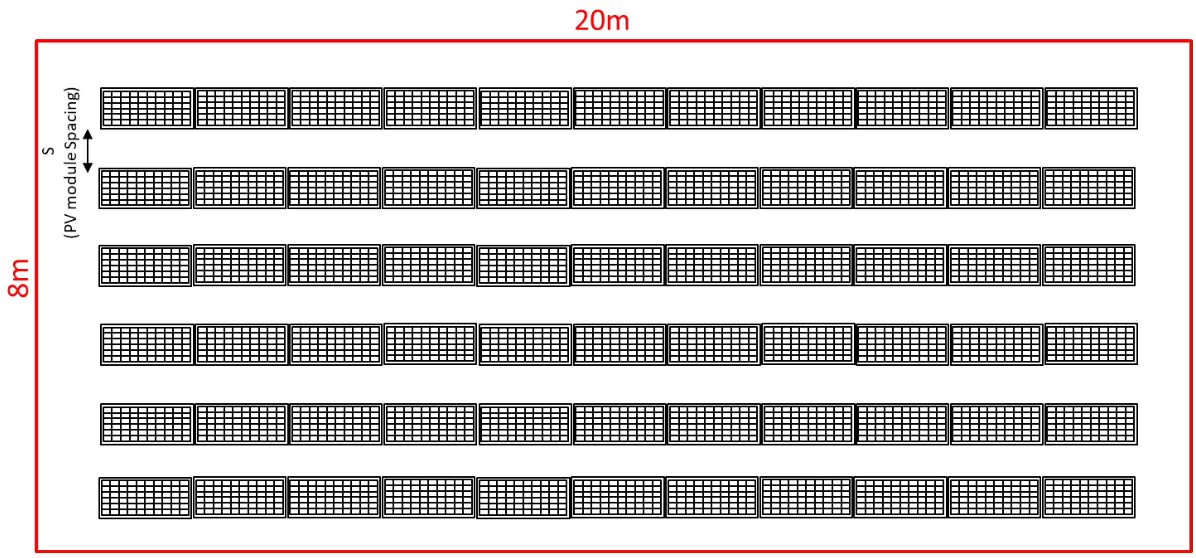


Figure 42 – PV modules layout in the available area

Having previously assessed an average yearly production of 1830 kWh/kW$_p$/year for the site and situation under study, this means, for the PV System, an average production of:

$$E = 1830 \text{ kWh/ kW}_p \text{ / year x } 19.8 \text{ kW}_p = 36234 \text{ kWh/year}$$

Which must then be consistent with the consumed energy.
The data of interest for the chosen PV modules, as expressed at STC are here listed:

Peak Power	300 W$_p$
Maximum System Voltage	1000 Vdc
Maximum Power Voltage V_{MPP}	32.6 V
Maximum Power Current I_{MPP}	9.19 A
Open Circuit Voltage V_{OC}	39.9 V
Short Circuit Current I_{SC}	9.64 A
Temperature coefficient of V_{OC} (β)	-0.116 V/°C
Max Series Fuse Rating	15 A

For this size of plant, the choice of a multi-string inverter is made (see Figure 27). This will be selected:

- to allow an input power at DC side of 19800 W$_p$;
- to have a MPPT range compatible with the strings of PV modules to be formed;
- to connect the Solar PV System to the 230/400VAc distribution network;
- to meet with SEC requirements (Technical Standards for the Connection of Small-Scale Solar PV Systems to the LV and MV Distribution Networks of SEC).

Choice of the inverter

The following choice is then made by combining the input data so far collected:

Number of modules	66
Module rated power (STC)	300 W_p
Array rated power	19800 W_p
Number of strings	3
Number of modules / strings	22

Inverter:

Input DC rated power	20440 W
Maximum input voltage	1000 Vdc
MPP Voltage Range	320 to 800 Vdc
Max. input current / MPPT	33 A
Number of independent MPPT	2
Number of independent MPPT used	1
Strings per used independent MPPT	3

The checks presented in 8.2.1 and repeated here for the specific case have to be carried out to confirm the choice of the inverter (this can also be done by proper sizing tools provided by inverter manufacturers).

The electrical characteristics of the string are (for the definition of symbols refer to 8.2.1):

- Maximum Open-Circuit (no-load) Voltage $V_{oc\ max}$ of the PV string

$$V_{oc\ max} = N_{mod} \times [V_{oc} + \beta \times (T_{min} - 25)] = 22 \times [39.9 + (-0.116) \times (0 - 25)] = 941.6\ V$$

- Minimum MPP Voltage of the PV string - V_{min}

$$V_{min} = N_{mod}\ [V_{MPP} + \beta \times (T_{max} - 25)] = 22 \times [32.6 + (-0.116) \times (80 - 25)] = 576.8\ V$$

- Maximum MPP Voltage of the Solar PV System - V_{max} (PV string)

$$V_{max} = N_{mod} \times [V_{MPP} + \beta \times (T_{min} - 25)] = 22 \times [32.6 + (-0.116) \times (0 - 25)] = 781\ V$$

The following checks have then to be made:

$V_{oc\ max\ of}$ the PV string at 0°C ≤ V_{MAX} (Inverter)	941.6 V ≤ 1000	VERIFIED
$V_{oc\ max\ of}$ the PV string at 0°C ≤ V_{MAX} (PV modules)	941.6 V ≤ 1000	VERIFIED
V_{min} of the PV string at 80°C ≥ $V_{MPPT\ min}$ (Inverter)	576.8 ≥ 320	VERIFIED
V_{max} of the PV string @ 0°C ≤ $V_{MPPT\ max}$ (Inverter)	781 ≤ 800	VERIFIED
I_{max} of the PV array /MPPT (*) ≤ $I_{max\ input}$ / MPPT (Inverter)	3 × 9.64 ≤ 33 A	VERIFIED

(*) Having assumed that all the 3 strings are connected to the same MPPT.

A) Case of strings directly connected to the inverter

With reference to the PV modules layout and the number of strings chosen, the subdivision of the modules to compose the strings can be as shown in Figure 43. The route of string cables is also shown in the same figure for further evaluation on string cables, by assuming that the inverter is installed in a technical room (e.g. the car garage) at the ground floor.

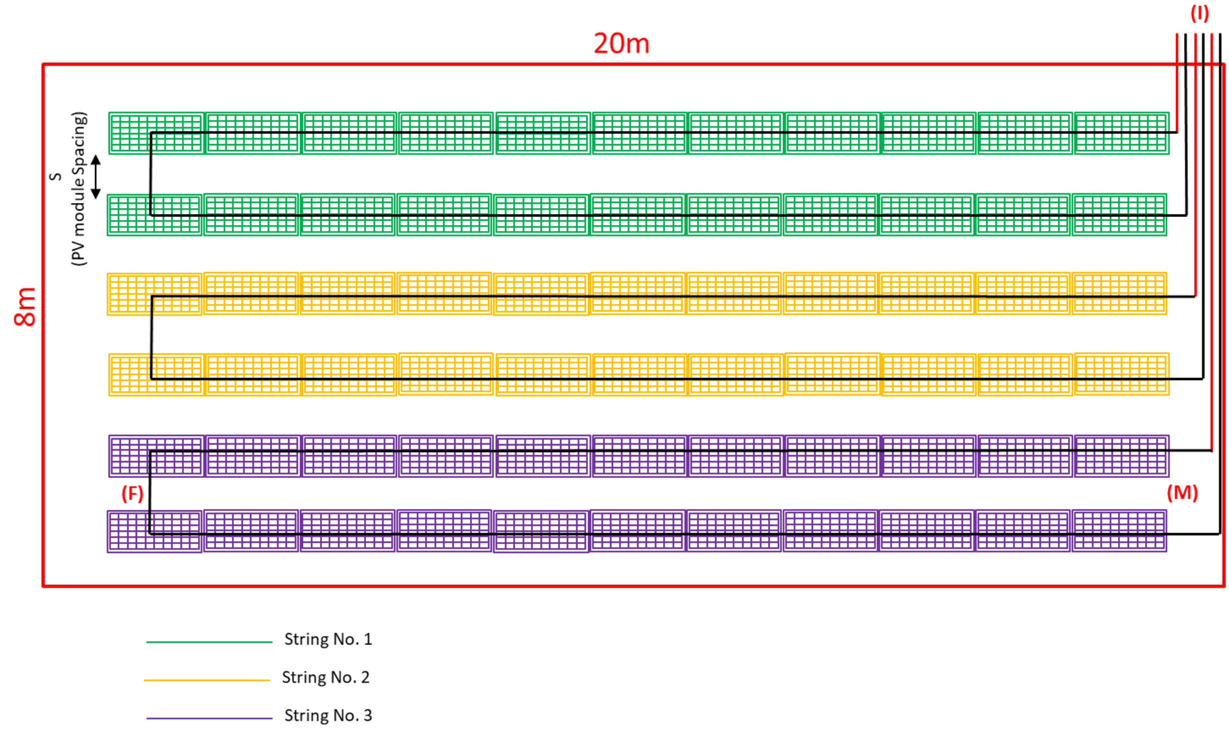


Figure 43 – Definition of the PV modules belonging to each string and string cable route

Choice of the DC cables

The string with the longest DC line (String No. 3 as evident in Figure 43) can be taken in consideration for the choice of the cross-section of string cables.

Let us assume that the distance from where the inverter is installed (I) to the furthest point (F) of String No. 3 is about 40 m. Two cables, for positive and negative poles respectively, will be routed along this path from (I) to (M), where they will be connected to cables attached on the rear of the PV Modules, with which the route between (M) and (F) and back to (M) is covered.

Therefore, the following condition is to be verified:

From / To	Distance (m)	Cross-sectional area (mm^2)	Type of cable	Laying
(I)/ (M)	20	6 (*)	Solar cable	In conduit and in trunking on the roof
(M) / (F)	20	4 (**)	Solar cable	In air in the rear of PV modules

(*) Cross-sectional area to be chosen by the designer and to be verified

(**) Cross-sectional area of the cables already attached to PV modules

The electrical data of the cables are the following:

Cable cross-section	Iz0 at Tamb = 30°C
4 mm^2	50 A
6 mm^2	64 A

As detailed in 8.2.2.3, the condition to be fulfilled for the choice of the string cable is:

$$I_z = I_{z0} \times k1 \times k2 \geq 1.35 \times I_{SC\_MOD}$$

This has to be verified for both the 4mm^2 cable and for the 6mm^2 cable.
By assuming:

Cable	Connection of PV Modules		Connection of PV Strings to Inverter	
Cable cross-sectional area	4mm^2		6mm^2	
I_{SC_MOD}	9.64 A	See PV module data-sheet	9.64 A	See PV module data-sheet
Iz0 at 30°C (Tamb)	50 A		64 A	
k1	0.41	Laying on the rear of PV modules in free air	0.73	Laying far from the PV modules (50°C), in conduit and in trunking on the roof
k2	1	Only one circuit	0.7	Derating factor due to proximity of 3 string cables

The condition $I_z = 50 \times 0.41 \times 1 = 20.5\ \text{A} \geq 1.35 \times 9.64 = 13.01\ \text{A}$
is fulfilled for the 4 mm^2 cable and
The condition $I_z = 64 \times 0.73 \times 0.7 = 32.7\ \text{A} \geq 1.35 \times 9.64 = 13.01\ \text{A}$
is fulfilled for the 6 mm^2 cable.

The voltage drop along these cables has then to be calculated for the longest string, to confirm the correctness of the chosen section. The formula suggested in 8.2.2.3, along with tables similar to that in Figure 29 apply, that is:

$$\Delta V\% = \left(\Delta V_{mV/m/A}(S_1) \times L_{\text{mod}-inv} + \Delta V_{mV/m/A}(S_{\text{mod}}) \times \frac{L_{\text{mod}}}{2} \right) \times \frac{P_{\max string}}{1000 \times V^2} \times 100$$

Where:

$\Delta V_{mV/m/A}$ = voltage drop per Ampère per meter as taken from a table like that in Figure 29
$P_{max\ string}$ / V = current in the string under verification
$L_{mod\text{-}inv}$ = is the length of the path between the PV modules and the inverter

L_{mod} = is the length of the cables already connected to the modules, summed up to compose the string. Usually, the PV Modules have two cable leads each one having a length of 1m. The total length to be considered in the formula would be in this case 2 leads × 1m × $N_{modules\,/\,string}$

The above quantities assume the following values:

	Value	Note
$L_{modules\text{-}inverter}$	20 m	Distance between the inverter installation place and the point where the connection with PV module cables is made
S_1	6 mm^2	Section under verification
L_{mod}	44 m	Given by the sum of lengths of cable leads attached to the PV module, i.e. 22 modules × 2 leads × 1m each
S_{mod}	4 mm^2	Cross-sectional area of PV modules cables
$P_{max\ string}$	6600 W	$=P_{mod} \times N_{mod/string} = 300W_p \times 22$ modules
V	717.2 V	$=V_{MPP}$ of a PV module × $N_{mod/string}$ = 32.6 × 22 V
$\Delta V_{mV/m/A}$	11 mV/A/m	Voltage drop (mV/m/A) for a 4mm^2 DC cable as taken from table in Figure 29
$\Delta V_{mV/m/A}$	7.3 mV/A/m	Voltage drop (mV/m/A) for a 6mm^2 DC cable as taken from table in Figure 29

Therefore:

$$\Delta V\% = \left(7.3 \times 20 + 11 \times \frac{44}{2}\right) \times \frac{6600}{1000 \times 717.2^2} \times 100 = 0.498\%$$

The application of the other suggested formula, that is:

$$\Delta V\% = \rho_{90°C} \times \left[\left(\frac{2 \times L_{modules-inverter}}{S_1} + \frac{L_{mod}}{S_{mod}}\right)\right] \times \frac{P_{max\ string}}{V^2} \times 100$$

Yields a similar result:

$$\Delta V\% = 0.023 \times \left[\left(\frac{2 \times 20}{6} + \frac{44}{4}\right)\right] \times \frac{6600}{717.2^2} \times 100 = 0.521\ \%$$

As the calculated voltage drop is < 1%, this is deemed to be acceptable and therefore the choice of the cable cross-sectional area is correct.

Protection of DC cables against overcurrent

In the case here described, the DC cables are directly connected from the string to a multi-string inverter, which is provided with internal overcurrent protections. No additional overcurrent protection devices are necessary in this case.

B) Case of string cables collected into a string-combiner box

To better illustrate, with an example, the criteria for the selection of the overcurrent protection as discussed in 8.3.2.2, let us assume that the string cables are instead collected in a String Combiner Box (SCB), as it would be the case of use of a central inverter. The situation is similar to that shown in Figure 30 and here repeated for the specific example.

The subdivision of the PV modules to form the strings does not vary with respect to the layout in Figure 42, only the way the cables are collected and grouped as shown in Figure 45.
The cable list becomes in this case the following:

From / To	Distance (m)	Cross-sectional area (mm^2)	Type of cable	Laying
(I)/ (SCB)	20	6 (*)	Solar cable	In conduit and in trunking on the roof
(SCB)/ (M)	4	4 (*)	Solar cable	In trunking on the roof
(M) / (F)	20	4 (**)	PV Module Cables	In air in the rear of PV modules

(*) Cross-sectional area to be chosen by the designer and to be verified
(**) Cross-sectional area of the cables already attached to PV modules, to be verified

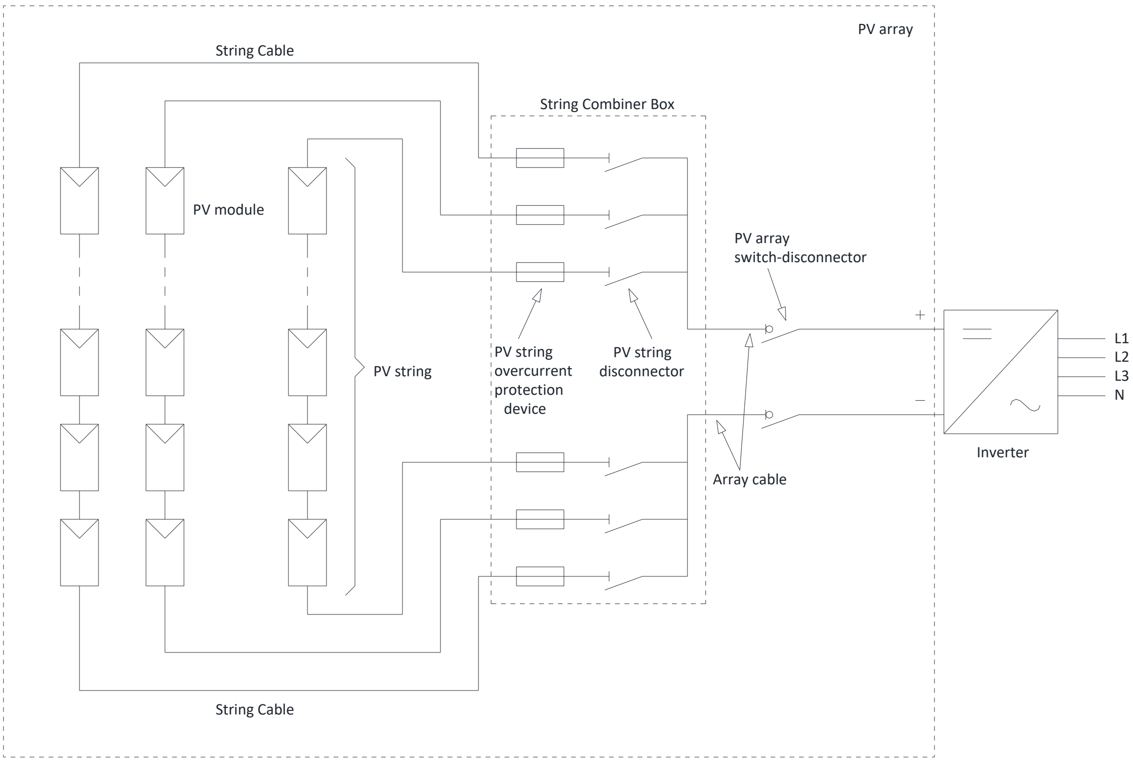


Figure 44 – Example of string collection into a string-combiner box for definition of overcurrent protections

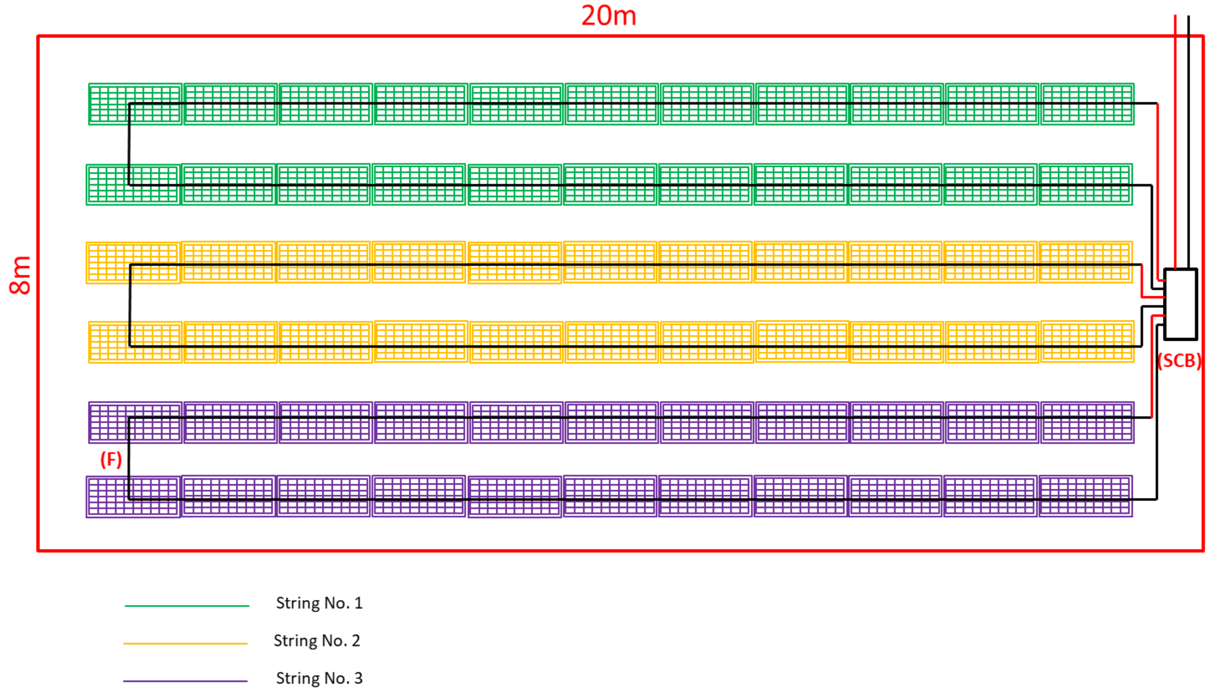


Figure 45 – Definition of the PV modules belonging to each string and string cable route

As detailed in 8.2.2.3, the condition to be fulfilled for the choice of the string cable is:

$$Iz = Iz0 \times k1 \times k2 \geq 1.35 \times I_{SC\_MOD}$$

This has to be verified for both the 4mm^2 cables and for the 6mm^2 cables.
By assuming:

Cable	Connection of PV Modules		Cable to connect the end of string to String Combiner Box	
Cable cross-sectional area	4mm^2		4 mm^2	
I_{SC_MOD}	9.64 A	See PV module data-sheet	9.64 A	See PV module data-sheet
Iz0 at 30°C (Tamb)	50 A		50 A	
k1	0.41	Laying on the rear of PV modules in free air	0.73	Laying far from the PV modules (50°C), in conduit and in trunking on the roof
k2	1	Only one circuit	0.7	Derating factor due to proximity of 3 string cables

The condition $Iz = 50 \times 0.41 \times 1 = 20.5\ A \geq 1.35 \times 9.64 = 13.01\ A$

is fulfilled for the 4 mm^2 cable which connects the PV modules and

The condition $Iz = 50 \times 0.73 \times 0.7 = 25.6\ A \geq 1.35 \times 9.64 = 13.01\ A$

is fulfilled for the 4 mm^2 cable to connect the end of the string to the String Combiner Box.

The current carrying capacity of the array cable which connects the String Combiner Box to the inverter, that is an Array cable in this case, has then to be verified with respect to the following input data:

Cable	Connection of String Combiner Box to the Inverter	
Cable cross-sectional area	6mm^2	
I_{SC_MOD}	9.64 A	See PV module data-sheet
Iz0 at 30°C (Tamb)	64 A	
k1	0.73	Laying far from the PV modules (50°C) in conduit or trunking
k2	1.0	No proximity with other cables in this case

The overall current which circulates in the Array cable between the String Combiner Box and the Inverter is the sum of the string currents, i.e.

$$Ib = 1.35 \times 3 \times 9.64 = 39.04\ A$$

The condition $Iz = 64 \times 0.73 \times 1 = 46.7\ A \geq 39.04\ A$

is then fulfilled for the 6 mm^2 cable.

The overall voltage drop can then be calculated for the longest string, to confirm the correctness of the chosen section. A formula like that suggested in 8.2.2.3 adapted for the case, along with the table in Figure 29 can be used:

$$\Delta V\% = \left(\Delta V_{mV/m/A}(S_1) \times L_{inv-comb\ box}\right) \times \frac{P_{\max array}}{1000 \times V^2} \times 100$$
$$+\left(\Delta V_{mV/m/A}(S_2) \times L_{comb\ box-string} + \Delta V_{mV/m/A}(S_{\text{mod}}) \times \frac{L_{\text{mod}}}{2}\right) \times \frac{P_{\max string}}{1000 \times V^2} \times 100$$

Where:

$\Delta V_{mV/m/A}$ = voltage drop per Ampère per meter as taken from a table like that in Figure 29

$P_{max\ array}$ / V = current in the array under verification

$P_{max\ string}$ / V = current in the string under verification

$L_{-inv-comb\ box}$ = is the length of the path between the inverter and the string combiner box

$L_{-\ comb\ box-string}$ = is the length of the path between the string combiner box and the PV modules

L_{mod} = is the length of the cables already connected on the modules, summed up to compose the string. Usually, the PV Modules have two cable leads each one having a length of 1m. The total length to be considered would be in this case 2 leads × 1m × $N_{modules\ /\ string}$ m

The below table summarize the following meaning and values of the different terms for the specific case:

	Value	Note
$L_{inverter\text{-}comb.box}$	20 m	Distance between the inverter installation place and the point where the connection with PV module cables is made
S_1	6 mm^2	Section under verification
$L_{comb.box\text{-}string}$	4 m	Distance between the installation place of the String Combiner Box and the point where the connection with PV module cables is made
S_2	4 mm^2	Section under verification
L_{mod}	44 m	Given by the sum of lengths of cable leads attached to the PV module, i.e. 22 modules × 2 leads × 1m each
S_{mod}	4 mm^2	Cross-sectional area of PV modules cables
$P_{max\ array}$	19800 W	$=P_{mod} \times N_{mod/array} = 300W_p \times 66$ modules
$P_{max\ string}$	6600 W	$=P_{mod} \times N_{mod/string} = 300W_p \times 22$ modules
V	717.2 V	$=V_{MPP}$ of a PV module $\times N_{mod/string} = 32.6 \times 22$ V
$\Delta V_{mV/m/A}$	11 mV/A/m	Voltage drop (mV/m/A) for a 4mm² DC cable as taken from table in Figure 29
$\Delta V_{mV/m/A}$	7.3 mV/A/m	Voltage drop (mV/m/A) for a 6mm² DC cable as taken from table in Figure 29

$$\Delta V\% = (7.3\times 20)\times\frac{19800}{1000\times 717.2^2}\times 100+\left(11\times 4+11\times\frac{44}{2}\right)\times\frac{6600}{1000\times 717.2^2}\times 100 = 0.929\%$$

Alternatively, the other suggested formula can be used:

$$\Delta V\% = \rho_{90°C}\times\left[\frac{2\times L_{inverter-comb.box}}{S_1}\times\frac{P_{max\,array}}{V^2}+\left(\frac{2\times L_{comb.box-string}}{S_2}+\frac{L_{mod}}{S_{mod}}\right)\times\frac{P_{max\,string}}{V^2}\right]\times 100$$

Which yields:

$$\Delta V\% = 0.023\times\left[\frac{2\times 20}{6}\times\frac{19800}{717.2^2}+\left(\frac{2\times 4}{4}+\frac{44}{4}\right)\times\frac{6600}{717.2^2}\right]\times 100 = 0.974\ \%$$

As the calculated voltage drop is < 1%, this is deemed to be acceptable and therefore the choice of the cable cross-sectional area is correct.

Use of a 10mm² cable for the connection from the String Combiner Box to the inverter can further reduce the voltage drop and, accordingly, the power losses.

Protection of DC cables against overcurrent

As more strings are connected to a Combiner Box, the condition:

$$((N_S - 1)\times I_{SC\_MOD}) > I_{MOD\_MAX\_OCPR}$$

needs now to be evaluated to determine if overcurrent protection is mandatory for the system.

As in the specific case:

N_S = number of strings in the array = 3
I_{SC_MOD} = 9.64 A
$I_{MOD\_MAX\_OCPR}$ = 15 A

And then ((3 – 1) × 9.64) > 15, overcurrent protection is necessary for each string.

The use of fuses is quite common for this purpose, and for the selection of the rated current the conditions described in 8.3.2.2 hold, that is:

$$I_n > 1.5 \times I_{SC\_MOD} \text{ and}$$
$$I_n < 2.4 \times I_{SC\_MOD} \text{ and}$$
$$I_n \leq I_{MOD\_MAX\_OCPR}$$

Which give:

$$I_n > 1.5 \times 9.64 = 14.46 \text{ A and}$$
$$I_n < 2.4 \times 9.64 = 23.14 \text{ A and}$$
$$I_n \leq 15 \text{ A}$$

A fuse with In = 15A is then suitable to protect each string (both cables and PV modules) against a short circuit. A fuse shall be installed both in the positive and in the negative cable.

Another condition to be verified is that the let-trough energy by the fuse at the short circuit current be smaller than the cable withstand, or, in other words

$$(I_{sc}^2 \times t) \leq K^2 \times S^2$$

As described in 8.3.2.4.
For the specific case of the string cable:
$S = 4 \text{ mm}^2$
$I_{sc} = 1.35 \times ((N_S - 1) \times I_{SC\_MOD}) = 1.35 \times 2 \times 9.64 = 26$ A
$K = 143 \text{ As}^{1/2}$
Therefore the fuse shall interrupt the short circuit current in less than

$$(t) \leq (1/I_{sc}^2) \times K^2 \times S^2 = (1/26^2) \times 135^2 \times 4^2 = 431 \text{ s}$$

Which is very likely to happen for the chosen fuse.

As regards the 6mm^2 array cable which connects the String Combiner Box to the Inverter, it can be noticed that the maximum short circuit current which this has to withstand is due to the contribution of all the 3 strings for a fault along the array cable, which is, as already calculated above:

$$Ib = 1.35 \times 3 \times 9.64 = 39.04 \text{ A}$$

As the cable has been chosen with a current carrying capacity Iz = 46.7 A > 39.04 A, the overcurrent protection can be omitted as stated in 8.3.2.

Selection of AC cable

The cable which connects the inverter to the Main AC (Eligible consumer LV) Panel of the installation will be chosen to meet with the following requirements:

- to carry a current Iz ≥ of the maximum AC current for the inverter, which is:

$$I_b = P_{nom\ inverter} / \sqrt{3}\ V_{nom} = 20000\ \text{VA} / \sqrt{3}\ 400\ \text{V} = 29\ \text{A}$$

- to limit the voltage drop along the line to max 1-2 %

The following choice is made, to be verified by calculation:

Cable type	Cu/XLPE/PVC Unarmoured
Cable voltage	0.6/1 kV
Cable arrangement	Four Core - 3ph + N
Cross-sectional area	16 mm^2
Iz in air at 40°C – In pipes	68 A (*)
Conductor resistance at 90°C (r_{cond})	2.45 Ohm/km
Cable reactance at 60Hz (x_{cab})	0.1147 Ohm/km

(*) Assuming that no proximity with other cables exist in the route between the inverter and the Main AC Panel

The condition

$$I_z = 68\text{A} \geq I_b = 29\ \text{A}$$

is fulfilled with this cable.

Voltage drop can be calculated by means of the following formula, by assuming that the inverter is working at a power factor of 0.95, as required by the Technical Standards for the Connection of Small-Scale Solar PV Systems to the LV and MV Distribution Networks of SEC:

$$\Delta V\% = \frac{1}{V_{nom}} \times \sqrt{3} \times \left(r_{cond} \times \cos\varphi + x_{cond} \times \sin\varphi\right) \times I_b \times L \times 100$$

Where:

V_{nom} = 400 V

cosφ = 0.95, sinφ = 0.312

L = 10 m (assumed as a distance between the Inverter and the Main AC Panel)

Which yields:

$$\Delta V\% = \frac{1}{400} \times \sqrt{3} \times \left(2.45 \times 10^{-3} \times 0.95 + 0.1147 \times 10^{-3} \times 0.312\right) \times 29 \times 10 \times 100 = 0.296\%$$

Which is acceptable.

Overcurrent protection of AC cable and Interface Switch

As also required by the Saudi Building Code (43-3.1), the operating characteristics of a device protecting a cable against overload shall satisfy the two following conditions:

$$Ib \leq In \leq Iz$$

$$I_2 \leq 1.45 \times Iz$$

Where:

Ib is the current for which the circuit is designed;

Iz is the continuous current-carrying capacity of the cable;

In is the nominal current of the protective device;

NOTE For adjustable protective devices, the nominal current In is the current setting selected if the protective device has a restricted access to its adjustable means. Restricted access shall be defined as the following:

- Removable and sealable covers over the adjusting means.
- Bolted equipment enclosure door.
- Locked doors accessible only to qualified personnel.

If the above conditions are not satisfied the nominal current In shall be the maximum settings possible.

I_2 is the current ensuring effective operation in the conventional time of the protective device. The current I_2 ensuring effective operation of the protective device is given in the product standard or may be provided by the manufacturer.

For instance, a 4-pole circuit breaker with a In = 50 A and thermal-magnetic release can suit in this situation, as:

$$Ib = 29\ A \leq In = 50\ A \leq Iz = 68\ A$$

NOTE: recommendations on the maximum size of the circuit breaker for inverter protection as given by manufacturers shall also be considered.

The protection against short circuit is then to be considered. The installation of a LV circuit-breaker requires that its short-circuit breaking capacity (or that of the CB together with an associated device) be equal to or exceeds the calculated prospective short-circuit current at its point of installation.

The installation of a circuit-breaker in an LV installation must fulfil one of the two following conditions:

- Either have a rated short-circuit breaking capacity Icu (or Icn) which is equal to or exceeds the prospective short-circuit current calculated for its point of installation, or
- If this is not the case, be associated with another device which is located upstream, and which has the required short-circuit breaking capacity

In the second case, known as “cascading” (or backup), the characteristics of the two devices must be co-ordinated such that the energy permitted to pass through the upstream device must not exceed that which the downstream device and all associated cables, wires and other components can withstand, without being damaged in any way.

The cascading of circuit breakers is to be carefully addressed with the help of coordination tables given by the manufacturers.
In this example and with reference to the scheme in Figure 47, the following situation can be considered:

- the main switch has to be a circuit breaker which can withstand the full prospective short-circuit current indicated by SEC at the Exit point;
- the circuit breaker dedicated to the protection of the line which connects the Solar PV System can be coordinated with the upstream main switch by considering the cascading between the two;
- proper care in the choice of an AC Contactor which is adequately protected against short circuit current has to be paid as explained in the following.

The cable is protected against short-circuit if the specific let-through energy of the protective device ($I_{sc}^2 \times t$) is lower or equal to the withstood energy of the cable ($K^2 \times S^2$) as already discussed also for DC cable protection.
In this case, however, the specific let-through energy of the protective device for the short circuit current declared by SEC at the Exit point will be retrieved from circuit breaker data sheets and compared with the withstood energy of the cable, i.e. 135^2 x 16^2 A^2s.
By assuming that the short circuit current declared by SEC at the Exit point is 20kA at 400 Vac, and that this is the short circuit current at the point of installation of the cable (in case, the actual short circuit current has to be calculated according to IEC 60909-0 standard), this yields:

$$t \le \frac{K^2 \times S^2}{I_{sc}^2} = \frac{135^2 \times 16^2}{20000^2} = 0.011s$$

A comparison of the energy withstood by the cable with the actual let-through energy by the circuit breaker, as given by the manufacturer, will show that the condition is fulfilled for this cross-sectional area and therefore the choice of the cable is correct.

The use of the above mentioned Automatic Circuit Breaker also with the function of Interface Switch for the Solar PV System is to discourage. In fact, in case the Interface Protection commands the opening of this due to a perturbance in the SEC Distribution Network, the Solar PV System will be disconnected from the network and this condition will remain unless a manual reclosure of the circuit breaker is operated or this circuit breaker is motorised. Therefore, as in common practice, the use of an AC3 contactor in addition is strongly recommended, which actually acts as Interface Switch and automatically recloses when the Interface Protection detects that the normal operating conditions of voltage and frequency have been re-established in the Distribution Network. The rating of the contactor can be the same as for the circuit breaker, i.e. 50A. Protection against short-circuit of this contactor shall be guaranteed by the upstream circuit breakers, therefore proper coordination between these shall be evaluated by means of tables provided by the manufacturers.

Protection against indirect contacts

As specified in 8.3.6.6, a Residual Current Device can be associated to the AC circuit breaker in the Eligible consumer LV Panel to protect the AC side of the Solar PV System against indirect contacts.

Two situations can occur:

1) the inverter cannot prevent DC fault currents entering the AC side of the system, therefore a Type B RCD is to be installed;
2) the inverter prevents any DC fault currents entering the AC side of the system, as usual for modern inverters, therefore a Type A RCD can be installed.

Considering that the installation is in a residential dwelling and that the distribution system is of TT type, the current of the RCD shall meet with the condition $Id \leq 50/R_E$ where R_E is the earthing resistance of the installation. If allowed by this condition, a current Id of at least 300mA is to be considered, to avoid nuisance tripping of the RCD.

Overvoltage protection

The criteria as expressed in 8.3.7 apply. By assuming that the value of L_{crit} calculated in Table 5 holds, that is L_{crit} = 14 m, this critical length is exceeded by the length of DC cables, as the distance between the inverter and the modules is of about 40 m.
Therefore, the installation of SPDs with the criteria shown in 8.3.7.4 is necessary.

With reference to Table 1 and to Figure 38, the following choice can be made:

SPD in Figure 38	Installation location	SPD Type	Note
1	In the inverter or in a specific panel at the DC side	Type 2	To be adopted as the risk assessment in 8.3.7.2 results in a need for DC SPDs (i.e. $L \geq L_{crit}$)
2	In the string combiner box, or in any case near the PV modules	Type 2	To be adopted as the distance between the PV modules and the inverter is > 10m
3	In the Main AC Panel	Type 1	-
4	In the inverter or in a specific panel at the AC side	Type 2	Not necessary, as the distance between the inverter and the Main AC Panel is < 10m

To be noticed that, as an SPD is required near the PV modules due to the distance between these and the inverter, a containing box is needed. Therefore, the use of a String Combiner Box and then the option B) above illustrated can be the most suitable in this case.

Earthing and bonding

As discussed in 8.3.5, the following earthing connections shall be provided:

- PV Modules: the frame of the PV Modules shall be connected to earth via a $16mm^2$ conductor, assuming that this is also necessary for lightning protection. Bonding between the PV modules with the same conductor shall be made, that is:

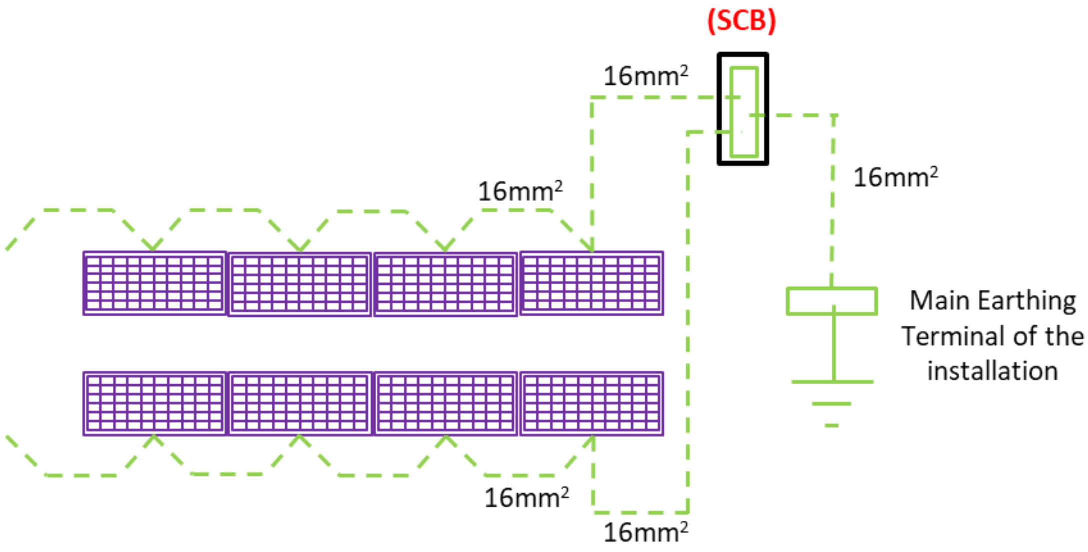


Figure 46 – Earthing and bonding

- Inverter: the exposed conductive part of the inverter shall be bonded to earth as required by the manufacturer

- AC side of the system: earthing shall be made as per normal rules in LV installations

Connection to SEC Distribution Network

The case under study is a sub-case of what represented in Figure 12 of Annex A in the Technical Standards for the Connection of Small-Scale Solar PV Systems to the LV and MV Distribution Networks of SEC. In fact, it is a Small-Scale Solar PV System with Maximum Connected Capacity > 11kW and ≤ 20kW with only one multi-string inverter, therefore the single line diagram becomes as shown in Figure 47.

Therefore, in addition to what described so far:

- an Interface Protection is required to operate on the Interface Switch, represented by the circuit breaker in the Main AC Eligible consumer LV Panel above sized. The contactor will then be provided with an undervoltage release. The characteristics of the Interface Protection can be found in the Technical Standards;
- a bidirectional meter needs to be installed by SEC at the Exit point.

Characteristics of equipment

The equipment to be installed at the DC side of the system (disconnectors, switch-disconnectors, fuses, etc.…) shall be suitable for use in this kind of systems and with the maximum voltage of the system itself, which is 1000 Vdc.

Fuses for string overcurrent protection shall be type “gPV”, specific for application on PV systems and with a maximum Vdc = 1000 V.

Means of disconnection which cannot operate under load will clearly be indicated, and proper care in operating on DC switches shall be paid.

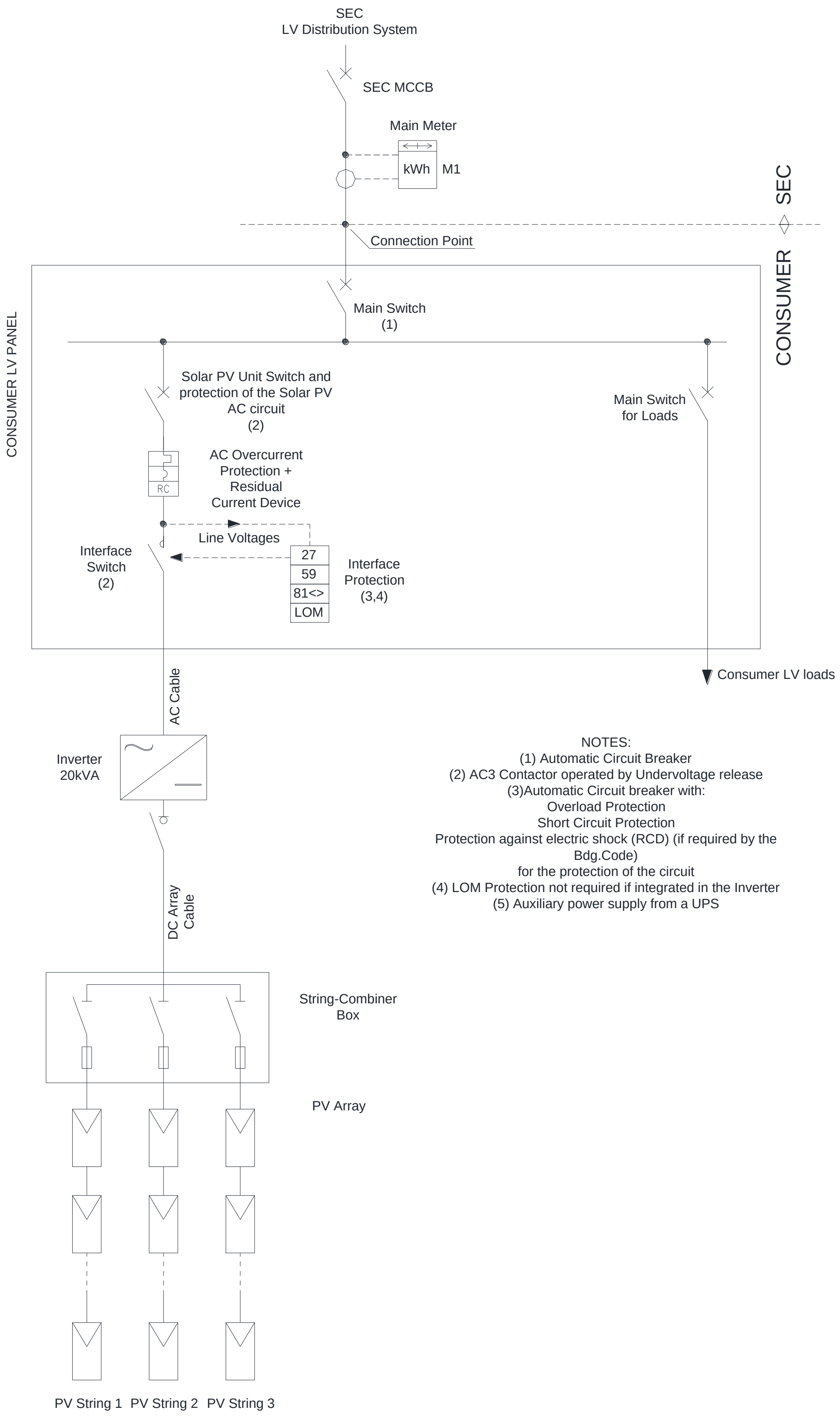


Figure 47 – Connection to SEC Distribution Network

ANNEX B. MORE REFERENCES

Books

- Guide to the Installation of Photovoltaic Systems - Published by the Microgeneration Certification Scheme ('MCS') (available on web)
- ABB Technical Application Papers No.10 - Photovoltaic plants - 2014 edition (available on web)
- Heinrich Häberlin, Photovoltaics: System Design and Practice - 2012 John Wiley & Sons, Ltd

Simulation Software

- PVSYST, PVsyst SA, Switzerland (license required)
- System Advisor Model , NREL, USA (registration required)

Solar tools - web applications

- http://re.jrc.ec.europa.eu/pvgis/ (PVGis)
- https://www.sunnydesignweb.com/sdweb/#/Home
- https://rratlas.kacare.gov.sa
- https://www.sunearthtools.com/dp/tools/pos_sun.php#top