TEXTBOOK

DESIGN OF PHOTOVOLTAIC POWER PLANTS

NTU “KhPI”
Kharkiv, 2024

MINISTRY OF EDUCATION AND SCIENCE OF UKRAINE

NATIONAL TECHNICAL UNIVERSITY
«KHARKIV POLYTECHNICAL INSTITUTE»

DESIGN OF PHOTOVOLTAIC POWER PLANTS

TEXTBOOK

for students of specialty
141 «Electric Power Engineering, Electrical Engineering and Electromechanics»

NTU "KhPI"
Kharkiv, 2024

MINISTRY OF EDUCATION AND SCIENCE OF UKRAINE

NATIONAL TECHNICAL UNIVERSITY
«KHARKIV POLYTECHNICAL INSTITUTE»

**A.V. Ivakhnov, O.V. Kulapin, K.V. Makhotilo, O.V. Bulhakov,
V.V. Hritsenko, D.A. Shokarov**

DESIGN OF PHOTOVOLTAIC POWER PLANTS

TEXTBOOK
for students of specialty
141 «Electric Power Engineering, Electrical Engineering and Electromechanics»

Approved by
Editorial and Publishing Board
of NTU «KhPI», minutes № 3
dated 24.10.2024 р

Kharkiv
NTU «KhPI»
2024

UDC 621.311.25
D46

Reviewers:

O. O. Miroshnik, Doctor of Engineering. Doctor of Physical Sciences, professor, Head of the Department Electricity Supply and Energy Management, State Biotechnological University, Kharkiv, Ukraine;

O. A. Plakhtii, PhD, associated prof., Department of Electrical Power Engineering, Electrical Engineering and Electromechanics, Ukrainian State University of Railway Transport, Kharkiv, Ukraine

Authors:

A.V. Ivakhnov, O.V. Kulapin, K.V. Makhotilo, O.V. Bulhakov,
V.V. Hritsenko, D.A. Shokarov

D46 Design of photovoltaic power plants : Textbook for students of specialty 141 «Electric Power Engineering, Electrical Engineering and Electromechanics» / A. V. Ivakhnov, O. V. Kulapin, K. V. Makhotilo, et al. – Kharkiv : NTU «KhPI». – 199 p.
ISBN 978-617-05-0517-0

The Textbook discusses the design of Photovoltaic Power Plants from the study of the solar insolation potential of the area, to the output of power to the grid. The DC and AC sides are discussed in detail. The main purpose of the manual is to help students gain knowledge about the design of photovoltaic power plants.

The textbook is recommended for students of specialty 141 «Electric Power Engineering, Electrical Engineering and Electromechanics»

Figures 97, Tables 60, Bibliography 45 titles.

ISBN 978-617-05-0517-0

UDC 621.311.25

CONTENTS

ACRONYMS

AC	– Alternating Current;
DC	– Direct Current;
DHI	– Diffuse Horizontal Irradiance;
DNI	– Diffuse Horizontal Irradiance;
GHI	– Global Horizontal Irradiation;
GTI	– Global Tilted Irradiation;
HV	– High Voltage;
IEA	– International Energy Agency;
IEC	– International Electrotechnical Commission;
IEEE	– Institute for Electrical and Electronic Engineers;
I-V	– Current–Voltage;
LS-PVPP	– Large-Scale Photovoltaic Power Plant;
LV	– Low Voltage;
LVS	– Low-Voltage Switchgear;
MS-PVPP	– Medium-Scale PV power plant;
MV	– Medium Voltage;
MW	– MegaWatt;
NEC	– National Electrical Code;
NREL	– National Renewable Energy Laboratory;
NPR	– Nominal Power Ratio;
NZE	– Net-Zero Emissions;
OCV	– Open-Circuit Voltage;
O&M	– Operations and Maintenance;
PT	– Potential Transformer;
PV	– Photovoltaic;
P-V	– Power–Voltage;
PVC	– Polyvinyl Chloride;
PVPP	– Small-Scale PV Power Plant;
SCC	– Short-Circuit Current;
SLD	– Single-Line Diagram;
SPD	– Surge Protective Device;
STC	– Standard Test Condition;
TSI	– Total Solar Irradiance;
VLS-PVPP	– Very Large-Scale PV Power Plant.

INTRODUCTION

Methodical instructions are aimed to help students successfully make diploma paper preparations. Here you can find instructions for calculations and formatting of diploma papers

Specialties of the Department "Energy Management" and "Power Plants" belong to the technical profile of training specialists with higher education.

The completion of diploma theses is the final stage of students' education in a higher education institution and aims to:

- consolidation and deepening of theoretical and practical knowledge in the chosen specialty and their application to solve specific problems;
- formation of skills in conducting independent research work and mastering the methodology of design or scientific research;
- acquisition of skills in generalizing and analyzing the results obtained by other developers or researchers;
- clarification of the student's readiness for independent work in the conditions of modern production, the progress of science, technology and culture.

The thesis is a qualification work of the graduate. Based on the level of performance of the thesis and the results of his (her) defense, the SEC concludes that it is possible to provide the graduate with the appropriate qualification.

The subject of the diploma works must be relevant, corresponding to the current state and prospects for the development of science, technology and culture.

Thesis topics and their supervisors are appointed by the graduating departments and approved by the council of the institute. When determining the topic, specific tasks in this area of training should be taken into account. The general list of topics of diploma theses is updated annually and brought to the attention of students in accordance with the established procedure.

The thesis is performed by the student within the period of time allotted for this by the curriculum in the relevant specialty.

Writing and design of the thesis should be carried out in strict accordance with the requirements for the design of text documentation (in compliance with the basic provisions of Standards and STHEI-KhPI).

These guidelines are intended for foreign students of the department

"Power Plants" (EPS), supervisors of theses, reviewers and members of the Government Examination Commission (GEC).

1 SOLAR PHOTOVOLTAIC POWER PLANT SYSTEM REVIEW

In the first chapter, in accordance with the assignment for the diploma thesis, a description of the locality/region/legislation specified in the task (structural units in the field of energy and renewable energy sources) is carried out.

1.1 PV System classification

1.1.1 Scale of system

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

1.1.2 Type of mounting system

The solar array can be either fixed mounted or mounted on a sun tracking system that follows the sun.

Two main types of tracking systems are available:

- one axis of rotation: the azimuth of the modules changes during the day according to the sun position.
- two axes of rotation: the azimuth and tilt of the modules change during the day according to the sun position.

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

1.1.3 Mounting system

1.1.3.1 Ground mounted

Ground-mounted PV systems are usually utility-scale photovoltaic plants. The PV array consist of PV modules held in place by racks or frames fixed on the ground with different kind of foundations:

- Earth screw foundation: this type of foundation could be used on soft soils or landfill sites stone-less with a low anchoring depth of 0.8 m;
- Pre-cast concrete blocks: this type of foundation could be used on bedrock areas, lands with little load-bearing capacity, landfill with very shallow anchoring depth, landfill area with stone cover and industrial wasteland with reinforced surface areas;
- Cast-in-place concrete: this type of foundation could be used on bedrock areas, lands with little loadbearing capacity, landfill with very shallow anchoring depth, landfill area with stone cover and industrial wasteland with reinforced surface areas;
- Pile-driving with pre-drilling: this type of foundation could be used on near-surface bedrock zone;
- Pile-driving with concrete collar: this type of foundation could be used on soils with little loadbearing capacity;
- Pile-driving (pole stuck in the ground): this type of foundation could be used on soils that are suitable for pile-driving
- Concrete anchors on concrete surfaces: this type of foundation could be used on concrete-covered and/or conversion areas.

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

1.1.3.2 Rooftop-mounted

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

- Integrated PV System: the PV modules replace, either totally or in part, the function of the architectural elements in the buildings, elements as coverings and transparent or semi-transparent surfaces on coverings. The PV modules are designed and realized not only to carry out the function of producing electric power, but also have architectural functions, such as: mechanical rigidity or structural integrity; primary weather impact protection: rain, snow, wind, hail; energy economy, such as shading, daylighting, thermal insulation; fire protection;

noise protection; separation between indoor and outdoor environments; security, shelter or safety. This macro-typology can be defined BIPV (Building Integrated PV)11.

- Partially integrated PV System: the PV modules are applied on buildings and structures for any function and purpose without replacing the building materials of structures themselves. The modules are installed so as to be coplanar to the tangential plane or to the tangential planes of the roof up to a limited height. This macro-typology can be defined BAPV (Building Applied PV)12.
- Non-integrated PV System: the modules are positioned on the external surfaces of building envelopes, on buildings and structures for any function and purpose. The modules are not coplanar to the tangential plane or to the tangential planes of the roof.

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

1.1.3.3 Carport

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

1.1.3.4 Other architectural integration

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

1.2 Main components of a photovoltaic plant

1.2.1 Photovoltaic generator

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

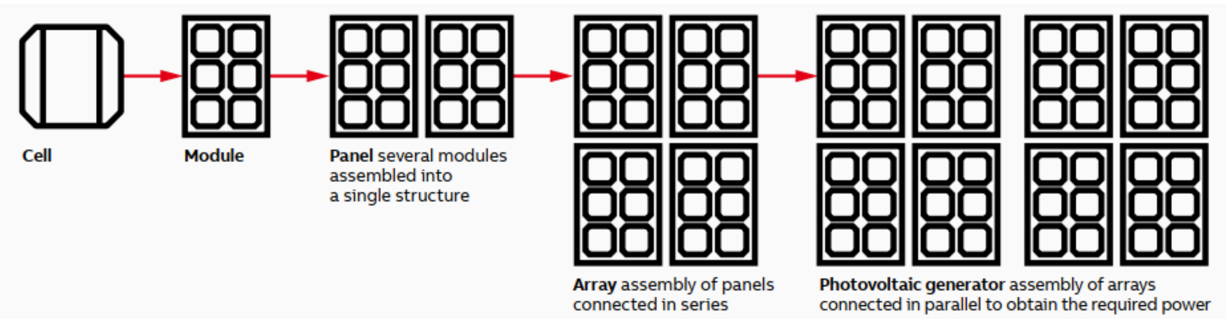


Figure 1.1 – Photovoltaic generator

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

In a series connection of cells / modules:

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

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

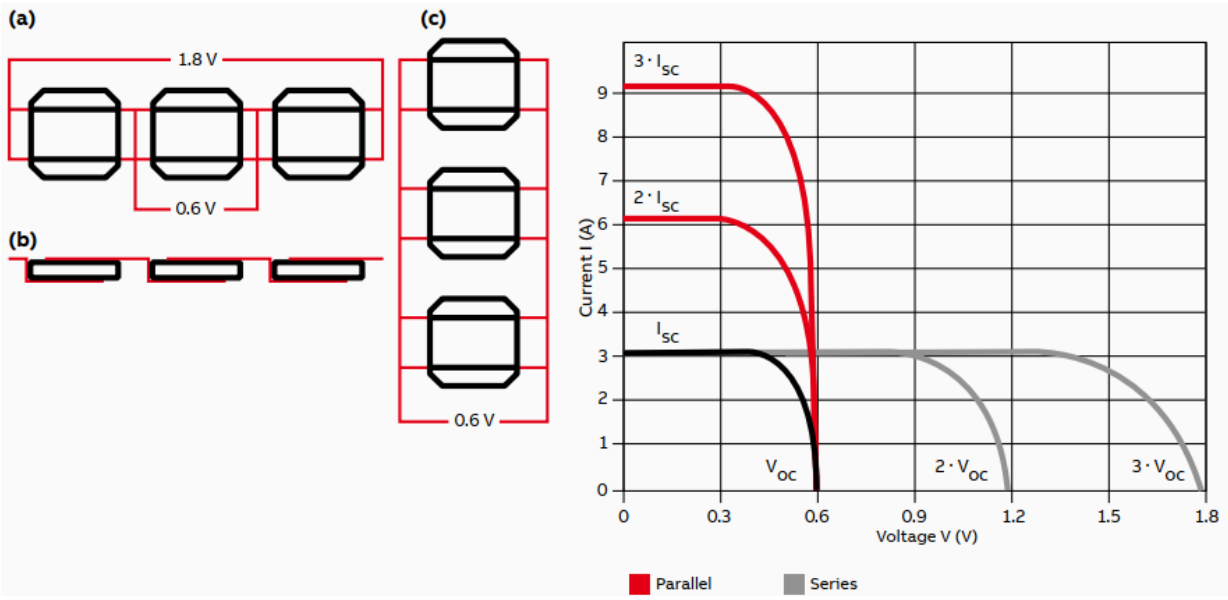


Figure 1.2 – Connection of PV modules

1.2.2 Inverter

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

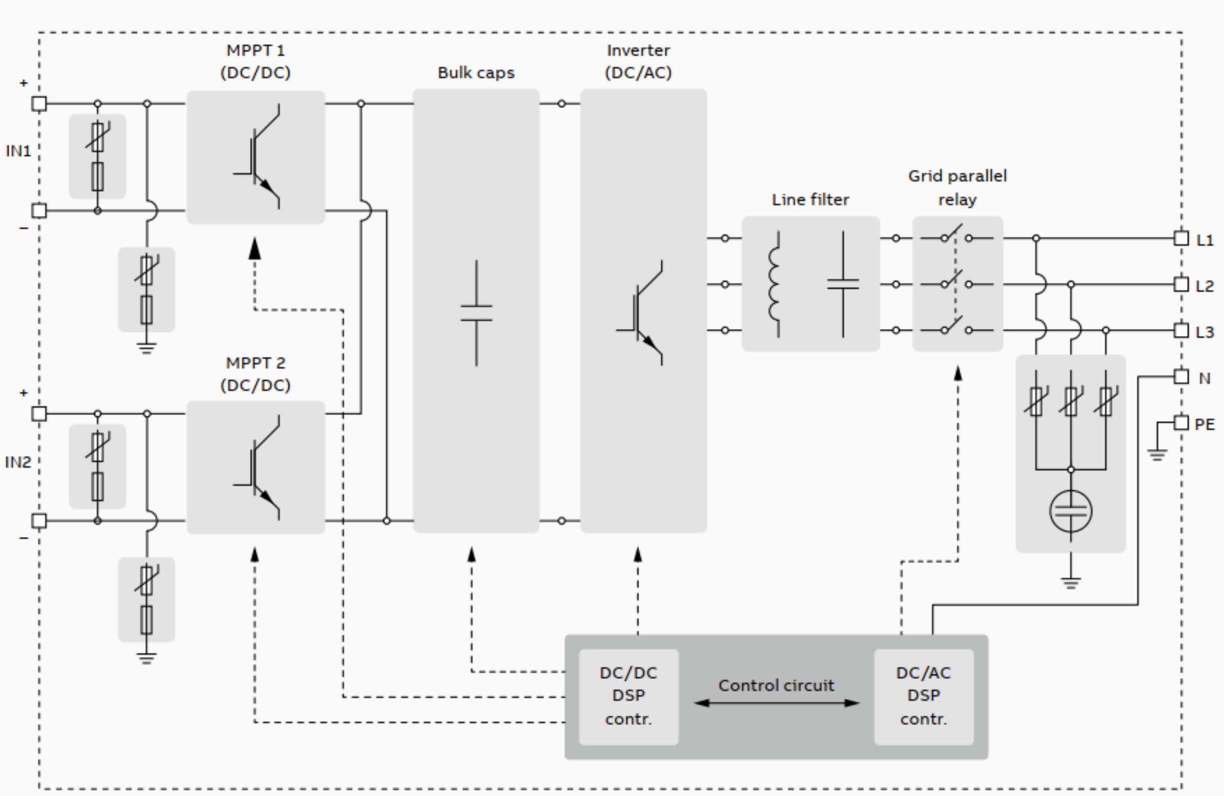


Figure 1.3 – The main parts that compose the inverters

- **MPPT** (Max power point tracker): it is a circuit (typically a DC to DC converter) employed in the photovoltaic inverters in order to maximize the energy available from the photovoltaic generator at any time during its operation. The power delivered by a PV generator depends on the point where it operates. Controllers can follow several strategies to optimize the power output of the photovoltaic generator. MPPT may implement different algorithms (e.g. Perturb and observe, Current sweep, Incremental conductance, Constant voltage, etc.) and switch between them based on the operating conditions of the photovoltaic generator.
- **Bulk capacitors:** Bulk Capacitors are used to prevent ripple currents from reaching back to the DC power source, and to smooth out DC bus voltage variations. They are also used to protect IGBTs.
- **DC/AC inverter:** the inverter is a circuit which converts a DC power into an AC power at desired output voltage and frequency. This conversion can be achieved by controlled turn on and turnoff devices (e.g. IGBT). The output voltage waveform of an ideal inverter should be sinusoidal. However, the voltage waveforms of the inverters are non-perfectly sinusoidal and contain harmonics. The output frequency of an inverter is determined by the rate at which the semiconductor devices are switched on and off by the inverter control circuitry. To

obtain a waveform as sinusoidal as possible, a more sophisticated technique – Pulse Width Modulation (PWM) – is used; PWM technique allows a regulation to be achieved on the frequency as well as on the r.m.s. value of the output waveform.

- **Line filter:** usually it is a L-C filter used in order to controls the quality of the output power to be delivered to the grid; the use of LC filter allows for generation of sinusoidal voltages with low harmonic distortion.

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

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

1.2.2.1 Centralized inverters

Central inverters are inverters up to 5000 kW (this up limit is growing continuously). The central inverter solutions can be used in PV power plants of commercial and industrial buildings and usually in ground mounted applications. The PV plant architecture with centralized inverter is described in Figure 1.4; this architecture requires the use of DC combiner boxes for the parallel of the PV strings.

The features and benefits of central inverters are:

- lower CAPEX;
- reduced number of inverters;
- more experience with on-field applications.

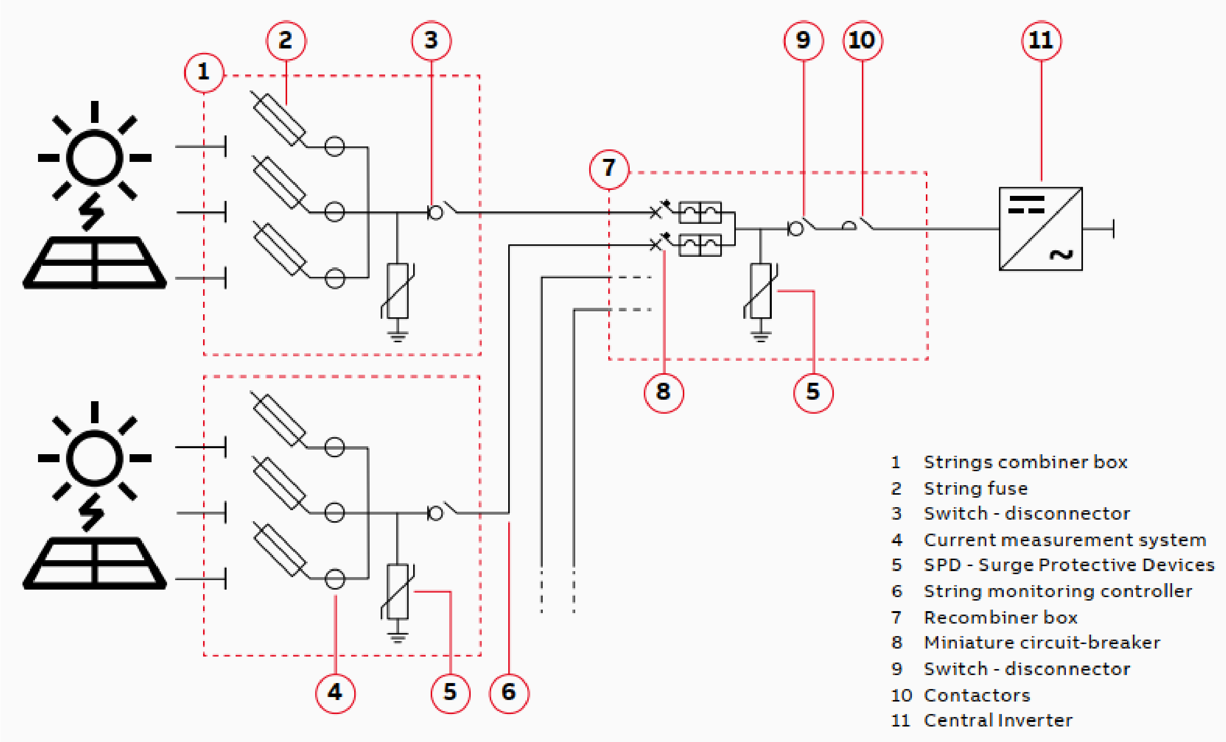


Figure 1.4 – The PV plant architecture with centralized inverter

1.2.2.2 String inverters

String inverters are inverters from 1.2 kW to 175 kW. The string inverter solutions can be used usually in PV power plants of residential, commercial and industrial buildings as well as in ground mounted applications. The PV plant architecture with string inverter is described in Figure 1.5.

The features and benefits of strings inverters are:

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

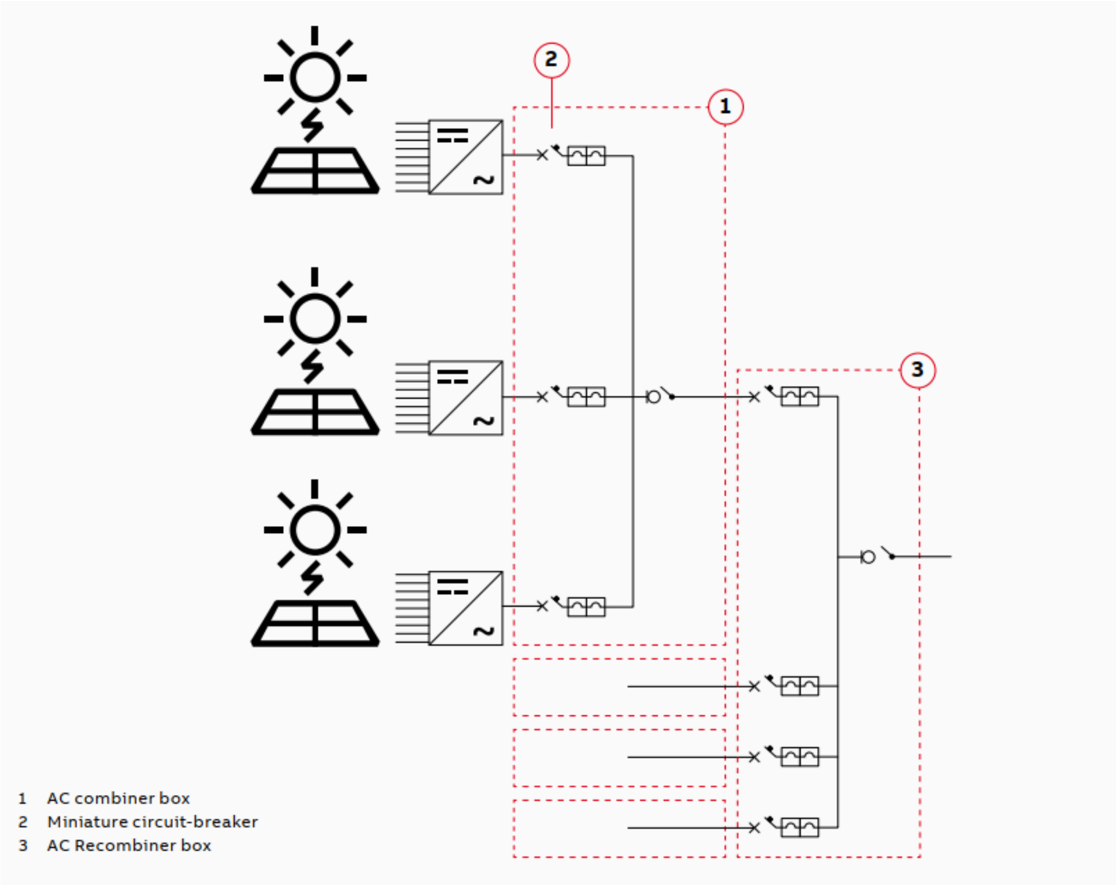


Figure 1.5 – The PV plant architecture with string inverter

1.2.2.3 Microinverters

Microinverters are installed behind 1 or few PV modules and convert the DC power from PV modules to grid-compliant AC power right at the module. The microinverter solutions can be used in PV power plants of residential and commercial buildings. The PV plant architecture with microinverter is described in Figure 1.6.

The advantages of micro-inverters are:

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

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

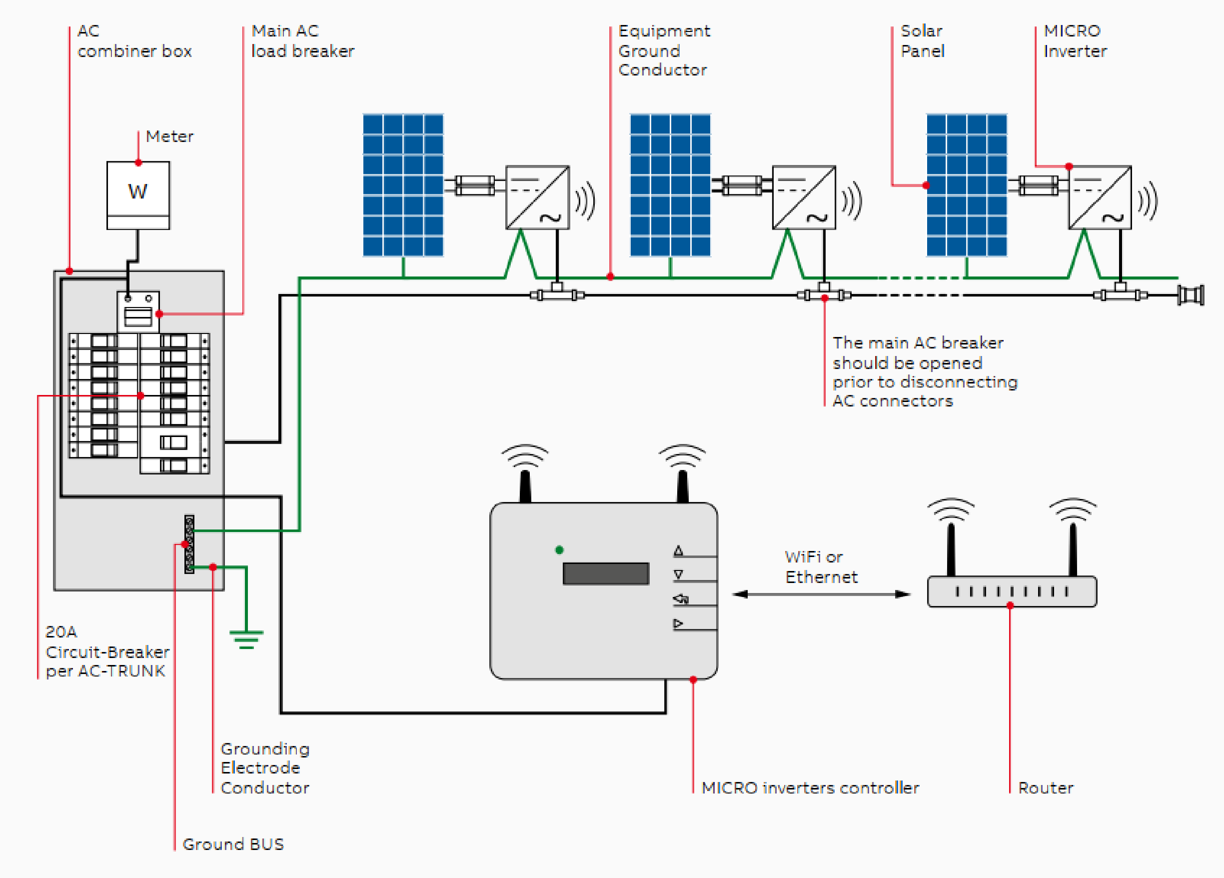


Figure 1.6 – The PV plant architecture with microinverter

1.2.2.4 Inverter Architecture Choice

The choice of inverter architecture impact on PV plant costs. Over the last few years, the costs of central and string inverters have closed dramatically. The cost of string inverters is still higher than central inverters (CAPEX Material Analysis).

The installation cost is also a driver for the choice of the inverter architecture: the mechanical installation, the electrical installation and the commissioning of string inverter is more expensive than that of the central inverters.

The DC BOS is more expensive for central inverter architecture and the AC BOS is more expensive for string inverters architecture. On a global level, the installation cost of string inverters is higher than that of centralized inverters.

The main difference between central and string inverters originates from operating costs:

- The large power capacity of central inverters leads to the need for active cooling. The smaller capacity of string inverters eliminates the need for active cooling.

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

From the plant performance point of view:

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

1.3 Types of photovoltaic modules

1.3.1 Crystal silicon modules

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

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

On Figure 1.7 in the left side a semi-square monocrystalline solar cell; in the right side a Square polycrystalline solar cell

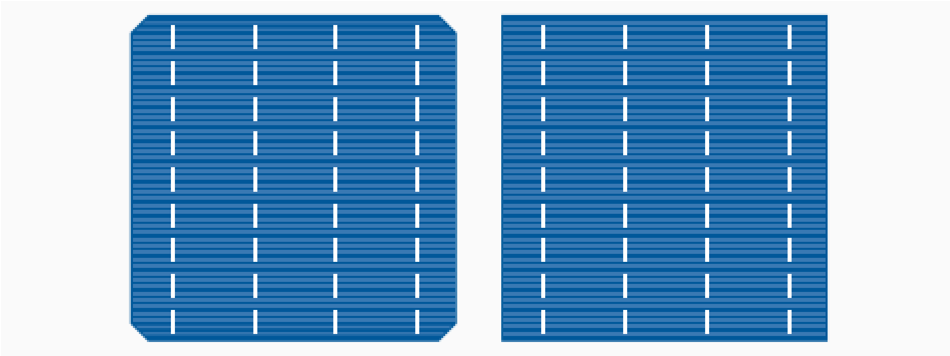


Figure 1.7 – Solar cells

• Cells dimension: the cells dimensions depend mainly from the silicon ingot used for the wafer production. Then the cells are categorized in 12.5 *cm* solar cells and 15.6 *cm* solar cells.

On the Figure 1.8 in the left side a 12.5 *cm* semi-square monocrystalline solar cell; in the right side a 15.6 *cm* semi-square monocrystalline solar cell.

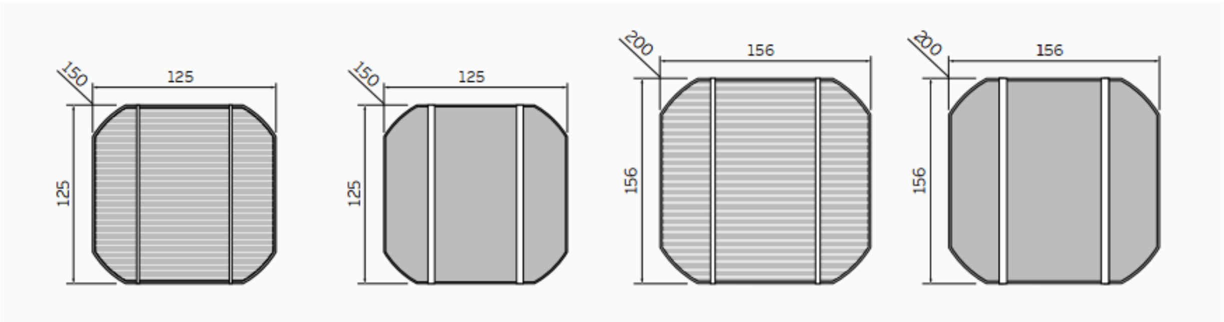


Figure 1.8 – Dimensions of solar cells

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

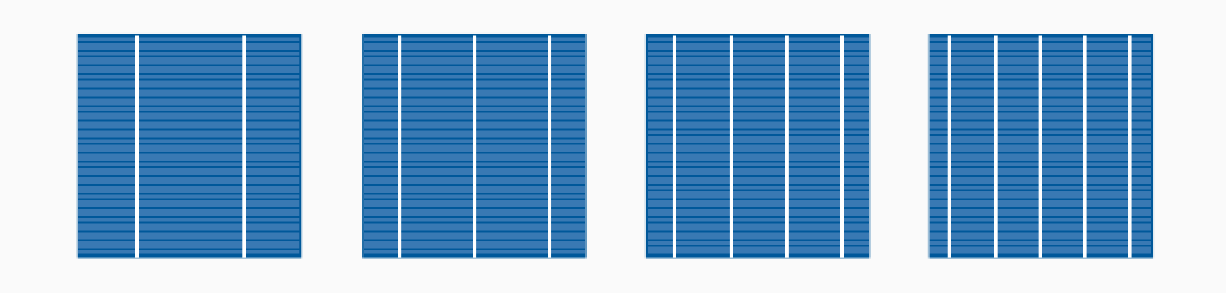


Figure 1.9 – Solar cells, from left to right: 2BB 6” polycrystalline solar cell; 3BB 6” polycrystalline solar cell; 4BB 6” polycrystalline solar cell; 5BB 6” polycrystalline solar cell

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

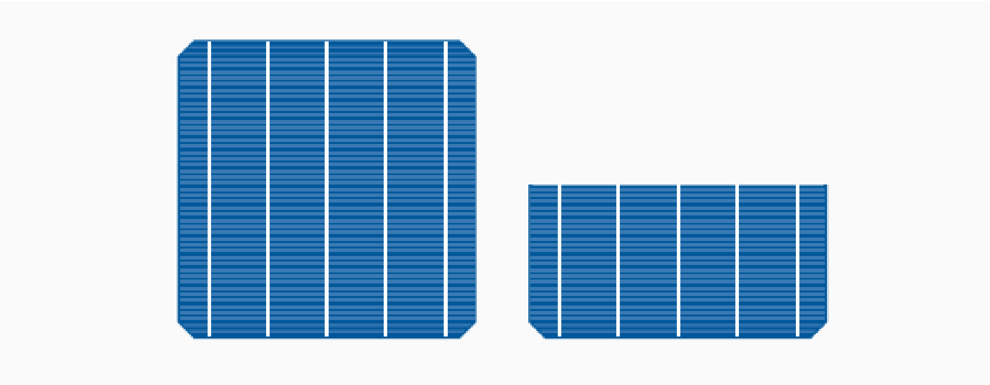


Figure 1.10 – Standard cells and half-cut cells

Other benefits introduced by half-cut cells are:

- better behaviour of module in case of shadow;
- reduced bypass diode activation;
- better protection against micro-cracks;
- cooler hot spots;
- optical gains from larger cell spacing.

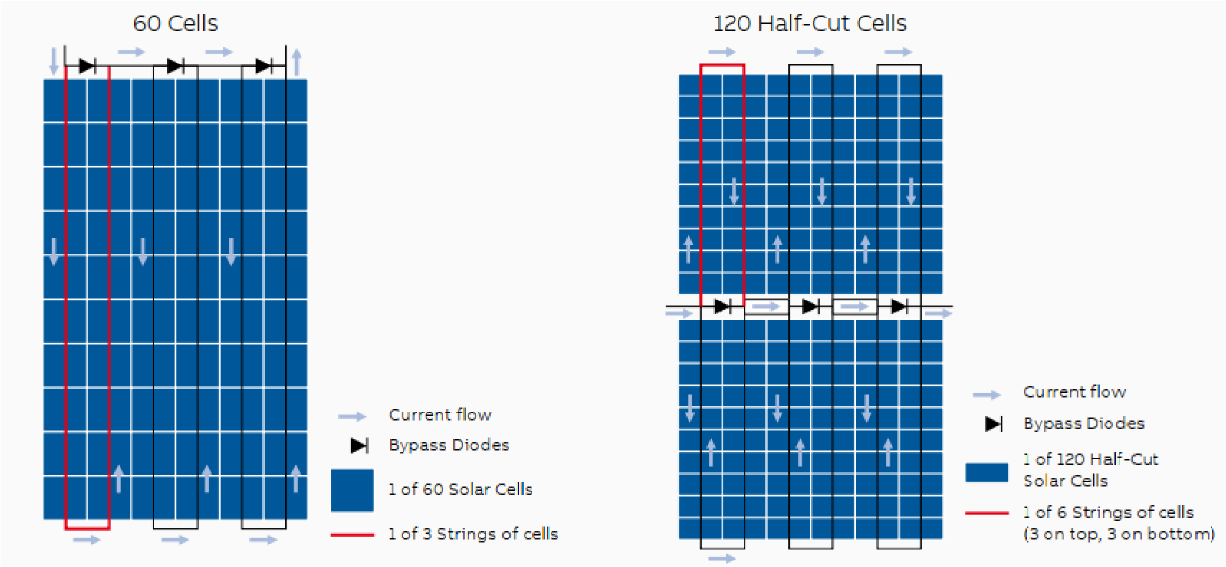


Figure 1.11 – Cells interconnection in a module built with standard cells on the left site; cells interconnection in a module built with half-cut cells on the right site

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

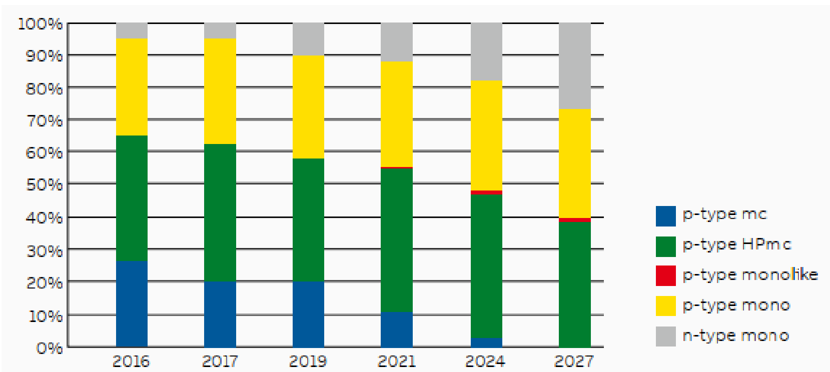


Figure 1.12 – Source International Technology Roadmap for Photovoltaic Results 2017

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

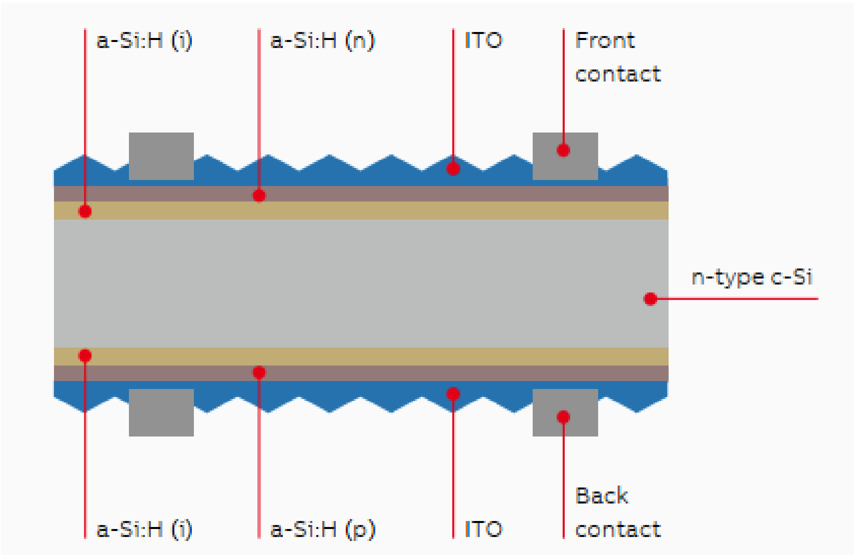


Figure 1.13 – HJT cell stratigraphy; source meyerburger.com

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

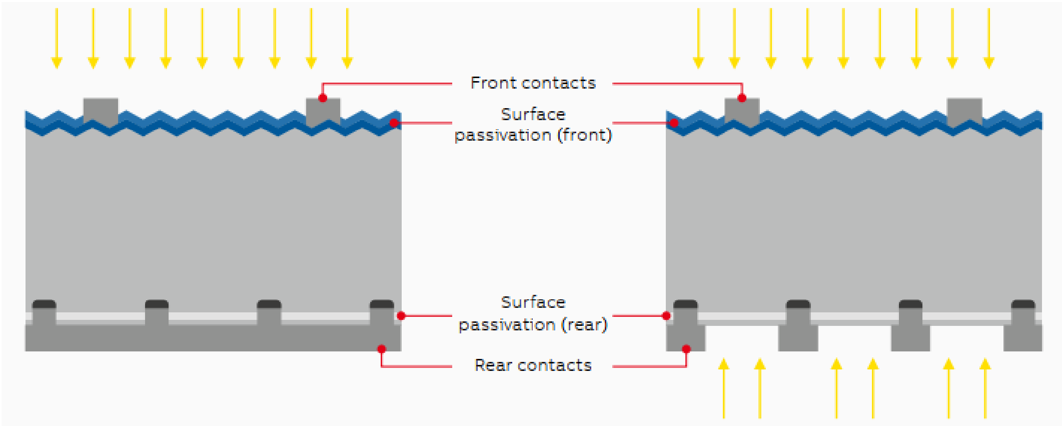


Figure 1.14 – A standard mono facial cell and a bifacial solar cell

The *bi-facial* modules are able to increase the energy yield of the PV installation.

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

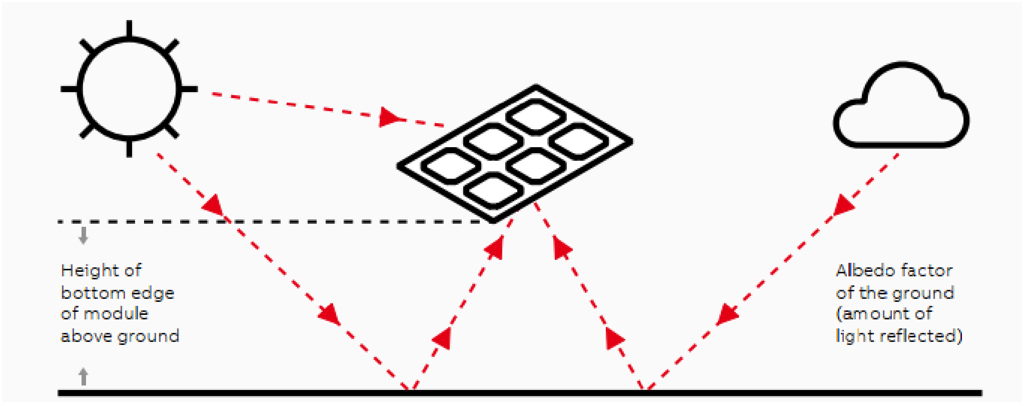


Figure 1.15 – Bifacial modules behaviour

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

The *c-Si* PV module most common layouts are:

• 60 6” cells in series connection;

• 72 6” cells in series connection;

• 120 half-cut cells.

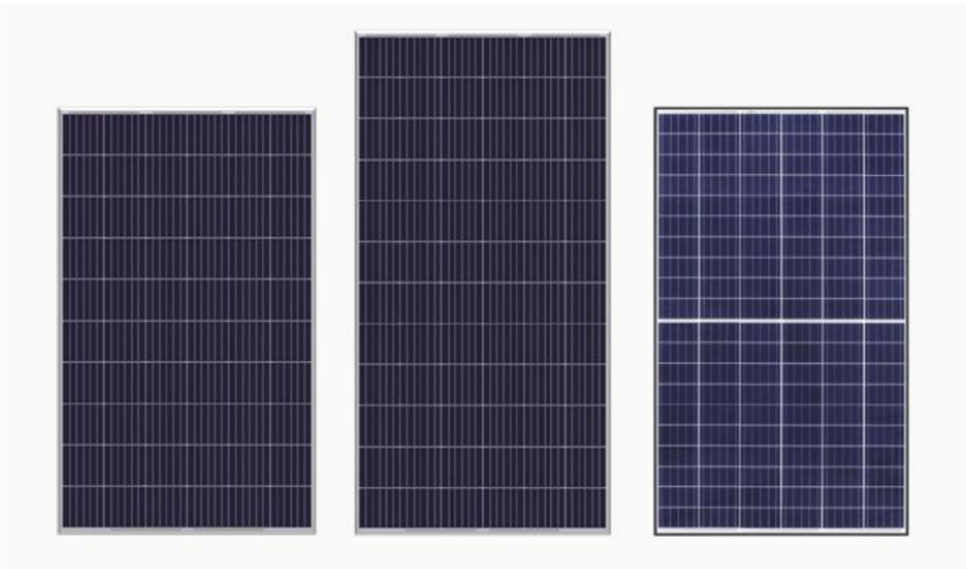


Figure 1.16 – The *c-Si* PV module most common layouts

In order to maximize the performance of the PV module, special technologies have been developed using the concept of rear contact solar cells. Rear contact solar cells achieve potentially higher efficiency by moving all or part of the front contact grids in the back side of the cells: the sunny side of the cells is not covered by metal paste for contacts purpose. There are several configurations of rear contact solar cells:

- Interdigitated back contact solar cells (IBC);
- Emitter wrap through (EWT);
- Metallization wrap through (MWT).

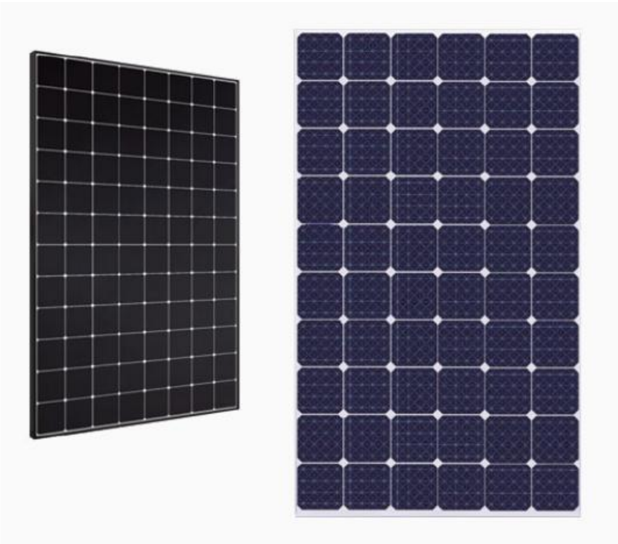


Figure 1.17 – PV module with IBC technology and PV module with MWT technology.

1.3.2 Thin-film modules

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

The materials mainly used are:

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

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

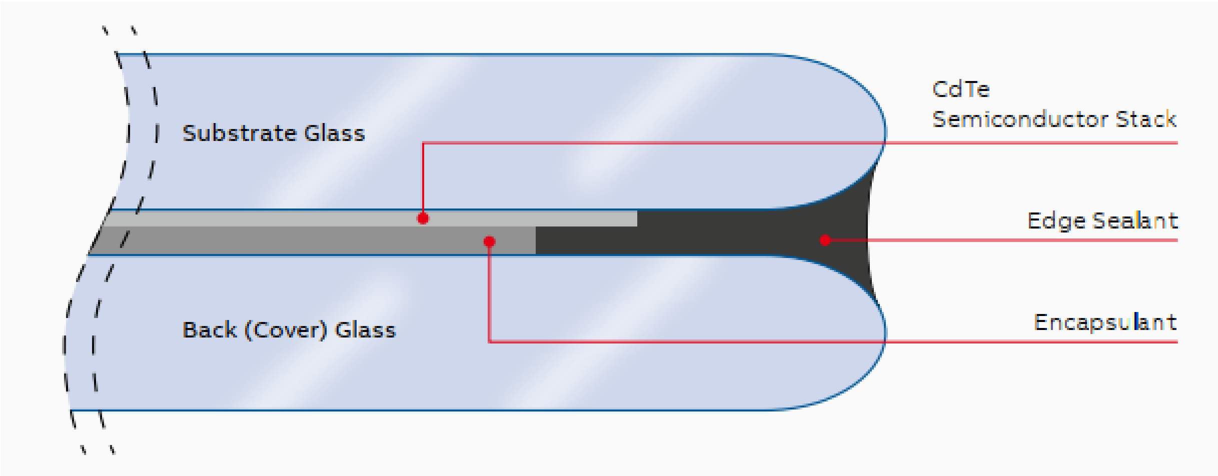


Figure 1.18 – Cross section of *CdTe* PV module

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

Figure 1.19 – *CdTe* PV module

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

1.4 PV plant layout

1.4.1 Type of installation

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

1.4.1.1 Decentralized distribution

Decentralized distribution is usually adopted in the PV plants where the photovoltaic generator is subject to different irradiation conditions (e.g. different tilt orientation of the PV modules; different azimuth orientation of the PV modules; part of the PV generator shadowed; etc.). using multiple inverters, Multiple MPPT inputs are available and then the different parts of the PV files subject to different irradiation condition could be connected to different MPPT.

Moreover, generally the conversion efficiency of string inverters is higher that the centralized inverter. Nowadays several string inverters have the fuses and

DC switch included, so the DC combiner boxes are not required in the PV installation. The use of string inverter implies that the AC outputs of the inverters are combined in the AC combiner boxes as shown on Figure 1.5. The AC combiner boxes usually contain fuse holders, SPDs and MCCBs. Decentralized distribution offers a very interesting pro: in case of inverter fault, only a portion of the PV generator is out of service and then the power production is not completely compromised and the uptime is maximized. Lastly the decentralized distribution offers a simple fault finding.

1.4.1.2 Centralized distribution

The centralized distribution is usually adopted in the large-size PV plants, where the photovoltaic generator is uniformly orientated. In the centralized distribution the PV modules strings, that compose the photovoltaic generator, are connected in parallel mode in the combiner boxes. The parallel of multiple combiner boxes is connected to the recombiner box and then to the central inverter.

The power distribution is achieved with DC cables. DC power distribution is more efficient and cheaper than AC because:

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

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

1.4.2 PV system design

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

- IEC 62548:2016 Photovoltaic (PV) arrays - Design requirements
- IEC TS 62738:2018 Ground-mounted photovoltaic power plants - Design guidelines and recommendations
- IEC 62817:2014 Photovoltaic systems - Design qualification of solar trackers

- NFPA 70: National Electrical Code Article 690, “Solar Photovoltaic (PV) Systems when the NEC first adopted Article 690.
- IEC 62446-1:2016 Photovoltaic (PV) systems - Requirements for testing, documentation and maintenance - Part 1: Grid connected systems - Documentation, commissioning tests and inspection

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

1.5 Shading

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

1.6 Algorithm

The Solar PV Plant design algorithm consists of the following stages, at each of which the following parameters are determined

I. Estimate of potential of installing Solar PV Plant at
   A. Selection of the area for the installation of PV power plants
   B. Estimation of solar insolation potential on select area
   C. Determination of temperature indicators for select area (T_{max}, T_{min})

II. DC side Solar PV Plant configuration
   A. Definition of Solar PV Plant topology ($P_{DC\ PV\ GEN}$)
   B. Choosing a PV module (P_{module}, $I_{MPP\ STC}$, $I_{SC\ STC}$, $U_{MPP\ STC}$, $U_{OC\ STC}$, α, β).
   C. Inverter power calculation and inverter selection ($P_{DC\ Max\ Inverter}$, $V_{min\ MPPT\ Inv}$, $V_{max\ MPPT\ Inv}$, $I_{max\ Inv}$, $I_{max\ MPPT\ Inv}$, $N_{input\ Inv}$, S_{Inv})
   D. Calculation of PV module voltage taking into account the temperature coefficient ($V_{oc\ MAX}$, $V_{MPP\ min}$).
   E. Calculation of the maximum number of PV modules combined in a string ($N_{MAX\ Module}$)
   F. Calculation of the minimum number of PV modules combined in a string ($N_{min\ Module}$)

- G. Calculation of the maximum current of the PV module of the temperature coefficient ($I_{SC\ MAX}$)
- H. Calculation of the maximum current string ($I_{sc\ MAX\ string}$)
- I. Calculation of the maximum number of strings that can be connected to the inverter ($N_{MAX\ Stirng}$)
- J. Calculation of Physical Parameters of PV Module Array (h, d, g)
- K. Development of a structural diagram of a PV power plant (N_{Stirng}, N_{Module})

III. Selection Equipment on the DC Side
- A. Selection of cable lines:
  1. Calculation of the permissible voltage drop at the site (ΔV)
  2. Calculation of the minimum cross-section of cable lines (S_{min})
  3. Long-term permissible current test (I_z)
- B. Choice of protection systems:
  1. Calculation and selection of fuses
  2. Calculation and selection of circuit breakers

IV. AC side Solar PV Plant configuration
- A. Choosing the type of transformer substation (N_{tr})
- B. Transformer Selection (S_{tr}, U_{LV}, U_{MV}, $u_{SC\%}$)
- C. Selection of a switchgear for power delivery to the grid (N_{TL})
- D. Overhead Power Delivery Line
- E. Calculation of short-circuit currents
  1. General information
  2. Equivalent scheme
  3. Components of Symmetrical Short Circuit Current (I_k'', i_p, i_A, $I_{k\tau}''$, B_k)

V. Selection of equipment on the variable stum side
- A. Circuit-breaker(s)
- B. Disconnectors
- C. Measuring current transformers
- D. Measuring Voltage Transformers
- E. Power Cables
- F. Flexible Busbars (Wires)

VI. Drawings
- A. Main Electrical Diagram (in which both parts DC and AC are shown)

Self-testing questions for Chapter 1

1) What is the purpose of rear contact solar cells in maximizing PV module performance?

2) How do thin film modules differ from crystalline silicon modules in terms of efficiency dependence on operating temperature?

3) Which surfaces can increase the energy gain of bifacial modules by certain percentages?

4) What are the common layouts for c-Si PV modules in terms of cell connections?

5) What are the different configurations of rear contact solar cells mentioned in the document?

6) How do the dimensions of solar cells vary based on the silicon ingot used for wafer production?

7) What are the key components involved in the overhead power delivery line for PV systems?

8) What are the considerations for selecting equipment on the variable stum side in a PV system?

9) What factors influence the albedo of the surface under a PV system?

10) How is the potential for installing a solar PV plant estimated, and what factors are considered in the process?

2 CALCULATIONS OF POWER ACCORDING TO INSOLATION'S, ANGLE AND TEMPERATURE

For calculations of Solar Power Plant data, we recommend to use Global Solar Atlas (GSA) from Recommended information sources . The primary aim of this Global Solar Atlas is to provide quick and easy access to solar resource and photovoltaic power potential data globally, at a click of a mouse. GSA layers and poster maps showing global, regional, and country resource potential can be found in the Download section. Further description of the data provided, the methodology for estimating solar resource potential, and guidance on how to use it, can be found in the Knowledge Base section. [1]

2.1 Methodology

The location-specific information provided by the Atlas involves three main different models:

- Solar radiation model
- Air temperature model
- PV power simulation model

Solar radiation and air temperature modeling result in a series of pre-calculated data layers that can be retrieved at (almost) any location on the map. Additional information about a possible PV system type and configuration are used for the PV power simulation, which is calculated on-demand using Solargis internal algorithms (Figure 2.1) and databases.

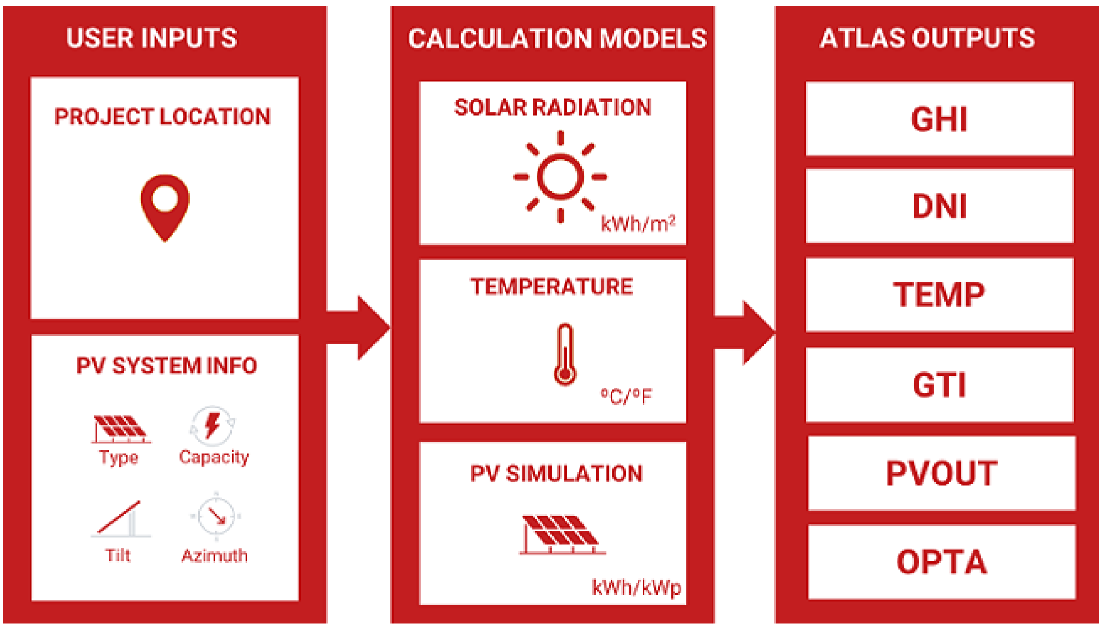


Figure 2.1 – Algorithm of taking data at Solar Atlas

2.1.1 Solar radiation model

The methods used in the solar radiation model (Figure 2.2) take into account the attenuation factors of solar radiation on the way through the atmosphere until reaching the ground surface. To calculate solar resource parameters, the Solargis model uses:

- data inputs from geostationary satellites
- meteorological models

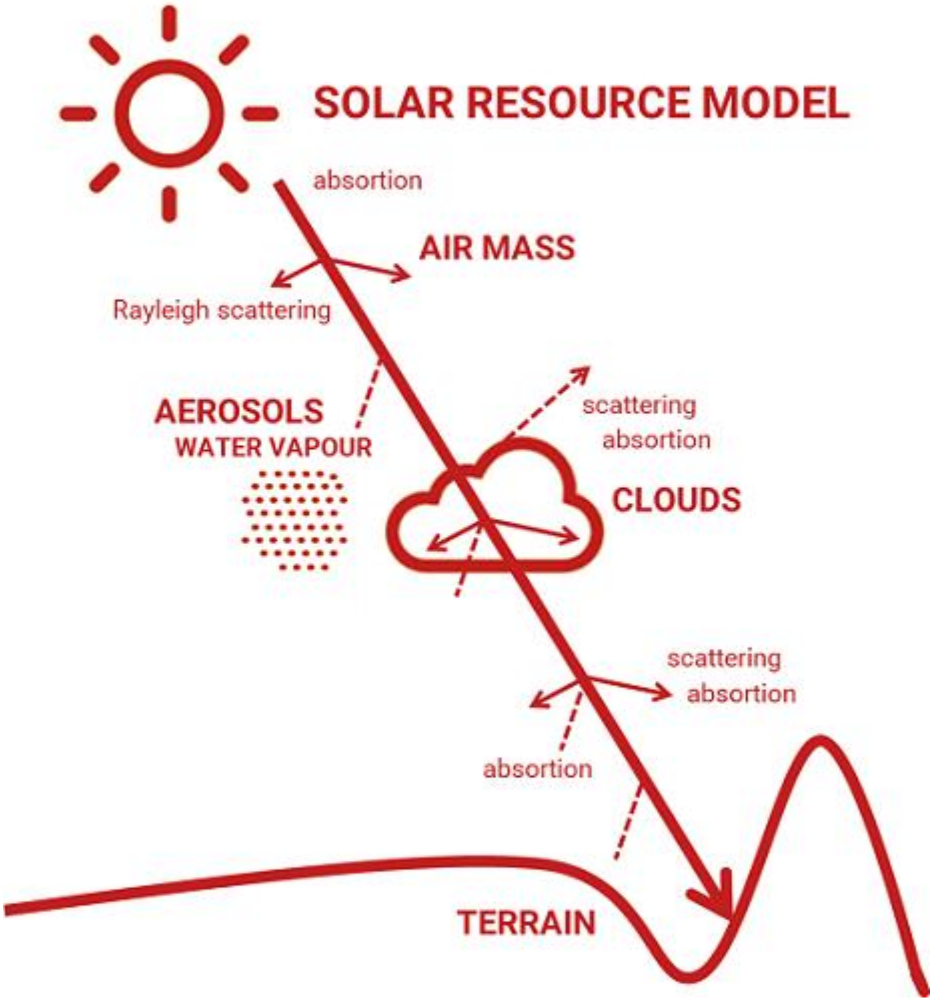


Figure 2.2 – Solar resource model

First, clear-sky irradiance (values under the assumption of absence of clouds) is calculated using the clear-sky model, which considers the position of the sun at every instant together with the effect of altitude, concentration of aerosols (particles coming from different sources, natural and human), water vapour content, and ozone. Second, the data from geostationary meteorological satellites (from several satellite missions covering different parts of the Earth) is used to quantify the attenuation effect of clouds by means of cloud index calculation. The clear-sky irradiance calculated previously is then coupled with the cloud index to retrieve the all-sky irradiance values. The primary calculated global horizontal irradiance is further post-processed by other models to get direct and diffuse irradiance and global irradiance on tilted surfaces. These values are corrected for shading effects from the surrounding terrain.

In the text on this website the terms solar resource or solar radiation are substituted by two terms: (i) solar irradiance, denoting radiant flux (power) per unit surface area, with typical unit W/m2; and solar irradiation, denoting energy or integral of solar irradiance over time, with typical unit Wh/m2.

The text below provides an overview of the introductory information. For a more complete description of the modeling approaches and related uncertainties please refer to the Solargis website.

2.1.2 Air temperature model

Meteorological parameters are also important, as they determine the operating conditions and performance efficiency of solar power plants. The reliability of meteorological data determines the accuracy of every solar energy assessment. Besides solar radiation, air temperature and consequently the temperature of PV modules, have the most relevance for the solar electricity simulation. In addition, wind speed, wind direction, relative humidity, and other parameters are also important. Most typically, meteorological data are not available for a particular site of interest, and the only option is to derive them from meteorological models. Modeled data has a lower accuracy (for a specific site) compared to the measurements from a well-maintained meteorological station with high-standard instruments. Thus, local values from the models may deviate from the local measurements and the uncertainty of the meteorological is of the same importance as for solar resource.

The meteorological data for global models have lower spatial and temporal resolution compared to solar resource modeled data. The data from global meteorological models have to be post-processed in order to provide parameters with local representation. The Global Solar Atlas works with data based on time series of air temperature data. The spatial resolution has been unified and enhanced by the Solargis disaggregation.

2.1.3 PV power simulation model

Electrical energy produced by a photovoltaic (PV) system depends on several external factors. Foremost of these is the amount of solar radiation falling on the surface of the PV modules, which in turn depends on the local climatic conditions as well as the mounting of the modules, e.g. fixed or tracking, inclination angle, etc. If solar radiation were the only parameter influencing the PV module's power output, the task of estimating the long-term energy performance of a system would be reduced to finding the average global in-plane irradiation. However, temperature is a crucial secondary component.

For each location selected by the user, multi-year, sub-hourly time series of solar radiation and air temperature data from Solargis are used as input for the calculations of the photovoltaic power production. From the original Solargis full-time series of data, statistically aggregated data is pre-calculated. For each month, a series of 7 percentile days in 15-minute time step is created for representing the range of conditions that are expected for each location in each month. After the simulation, a weighted average gives the final long-term monthly and annual output values. This approach is consistent in terms of space and time, and it is suitable for site prospection and pre-feasibility stage. The PV production is based on the start-up phase of a PV project, so the long-term performance degradation of PV modules is not considered.

Four main types of system can be selected from the Global Solar Atlas PV electricity calculation tab: small residential, medium-size commercial, ground-mounted large scale, and floating large-scale.

For a selected location, potential electricity production from the PV power system is calculated based on several conversion steps, as described below:

- Global irradiation falling on a tilted plane of PV modules is calculated from Global Horizontal Irradiance (GHI), Direct Normal Irradiance (DNI), terrain albedo, and sun position within a 15-minute time interval using diffuse irradiance model for tilted surfaces and angular reflection losses model.
- Shading by terrain features is calculated using high-resolution elevation data and calculated terrain horizon. Shading driven by buildings, vegetation and obstacles is not considered;
- The performance of PV modules is calculated by the implementation of Single-diode equivalent circuit simulation with De Soto five-parameter model. Parameters of generic crystalline-silicon modules are used. The module temperature is calculated from air temperature, effective GTI, thermal coefficient and PV module efficiency. Floating solar installations are treated as a different case, where PV module temperature is influenced also by water evaporation;
- PV field self-shading (inter-row shading) is caused by the arrangement of the modules in the rows. Modules, which are in the front row, cast

shadows on the back rows. Shading effect depends on PV module orientation (horizontal or vertical), strings layout and spacing between rows (defined by parameter Relative row spacing, which is a ratio between row – to – row distance and PV installation tables width). Inter-row shading losses are higher during seasons with low sun elevation angles and typically negligible during other seasons.

- DC to AC conversion losses is calculated by the implementation of Sandia Inverter Model, where inverter efficiency is modelled at the maximum power point of the connected PV module array.

The other losses, due to snow, dirt, dust, and longer-term soiling effects depend mainly on environmental factors and cleaning of the PV modules surface during the power plant lifetime. Other common losses are also influencing the final output, e.g. power tolerance of modules, mismatch, cable losses and power transportation losses.

2.1.4 Solar Radiation on a Tilted Surface

The power incident on a PV module depends not only on the power contained in the sunlight, but also on the angle between the module and the sun. When the absorbing surface and the sunlight are perpendicular to each other, the power density on the surface is equal to that of the sunlight (in other words, the power density will always be at its maximum when the PV module is perpendicular to the sun). However, as the angle between the sun and a fixed surface is continually changing, the power density on a fixed PV module is less than that of the incident sunlight.

The amount of solar radiation incident on a tilted module surface is the component of the incident solar radiation which is perpendicular to the module surface. The following figure (Figure 2.3) shows how to calculate the radiation incident on a tilted surface (S_{module}) given either the solar radiation measured on horizontal surface (S_{horiz}) or the solar radiation measured perpendicular to the sun ($S_{incident}$).

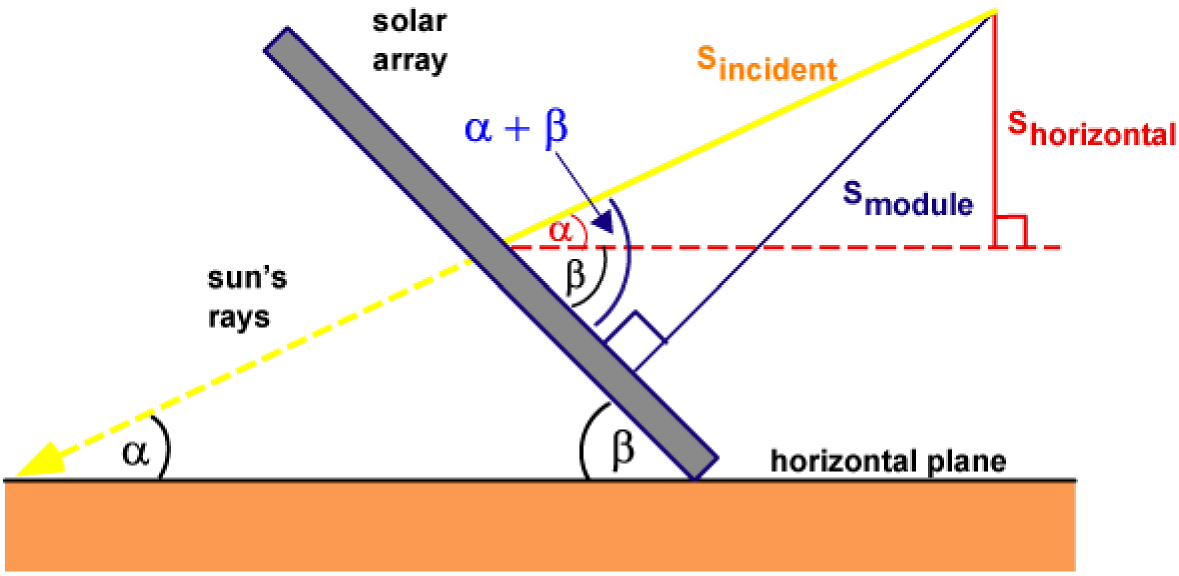


Figure 2.3 – Tilting the module to the incoming light reduces the module output.

The equations relating S_{module}, $S_{horizontal}$ and $S_{incident}$ are:

$$S_{horizontal} = S_{incident} \cdot \sin\alpha \tag{2.1}$$

$$S_{module} = S_{incident} \cdot \sin(\alpha + \beta) \tag{2.2}$$

where α – the elevation angle;
β – the tilt angle of the module measured from the horizontal.

The elevation angle has been previously given as:

$$\alpha = 90^\circ - \phi + \delta \tag{2.3}$$

where ϕ – the latitude;
δ – the declination angle previously given as:

$$\delta = 23.45^\circ \cdot \sin\left[\frac{360}{365} \cdot (284 + d)\right] \tag{2.4}$$

where d – the day of the year.

Note that from simple math $(284 + d)$ is equivalent to $(d - 81)$ which was used before. Two equations are used interchangeably in literature.

From these equations a relationship between S_{module} and $S_{horizontal}$ can be determined as:

$$S_{module} = \frac{S_{horizontal} \cdot \sin(\alpha + \beta)}{\sin \alpha} \quad (2.5)$$

The following active equations show the calculation of the incident and horizontal solar radiation and that on the module.

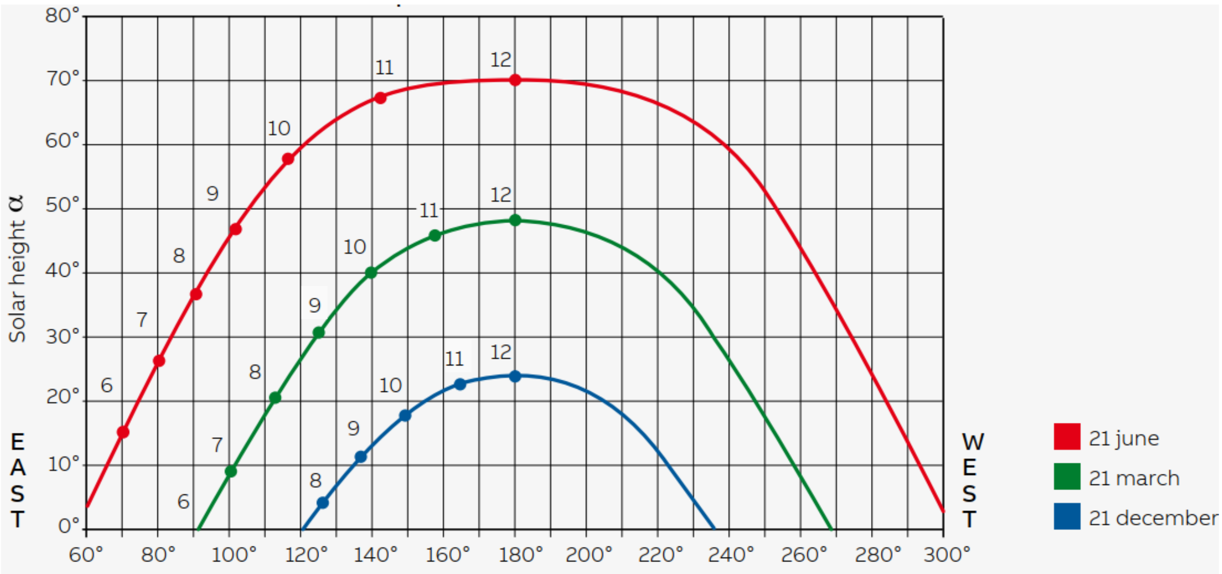


Figure 2.4 – Solar path at 45° North latitude

The tilt angle has a major impact on the solar radiation incident on a surface. For a fixed tilt angle, the maximum power over the course of a year is obtained when the tilt angle is equal to the latitude of the location. However, steeper tilt angles are optimized for large winter loads, while lower title angles use a greater fraction of light in the summer.

2.2 Getting started using GSA

2.2.1 Interactive maps

Interactive maps (Figure 2.5) allow visualization of solar resource potential for a region and provide annual average values for each map click.

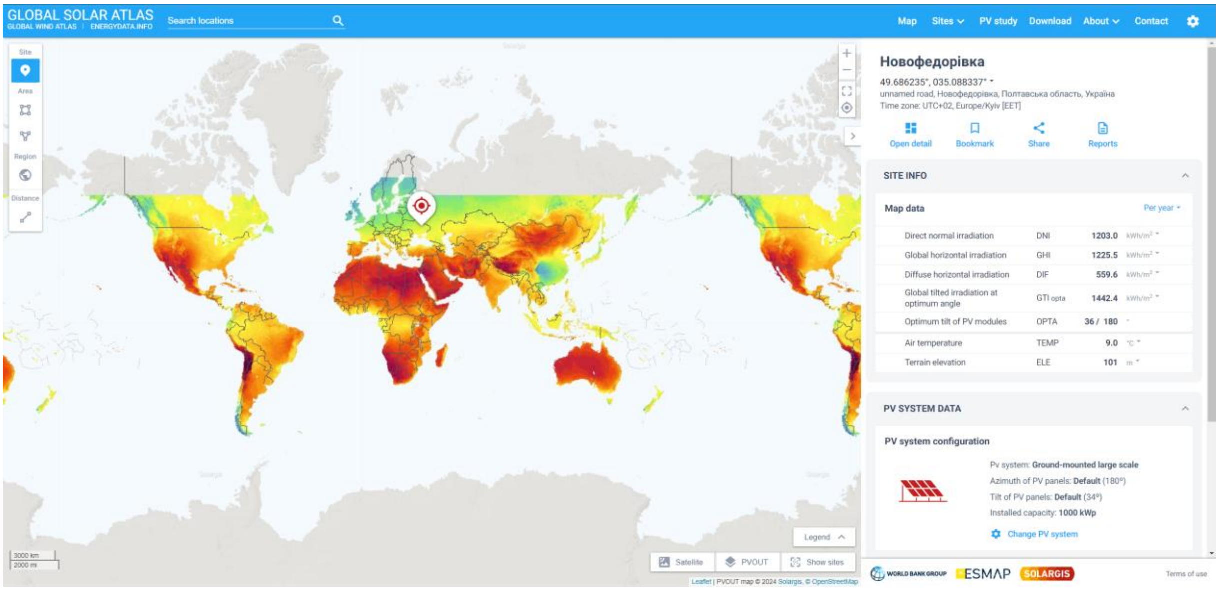


Figure 2.5 – Global Solar Atlas interactive map

2.2.2 PV energy yield calculator

PV yield calculator allows calculation of long-term energy yield for a custom-defined PV system (Figure 2.6). Energy yield estimates (Figure 2.7) are provided as 12x24 (month x hour) profiles allowing to understand seasonal and intra-day variability of PV production.

You are allowed to adjust the system according to your task (Figure 2.6), and get detailed data: map of irradiation, azimuth (Figure 2.8); power PV output of hourly profiles, monthly averages (Figure 2.9).

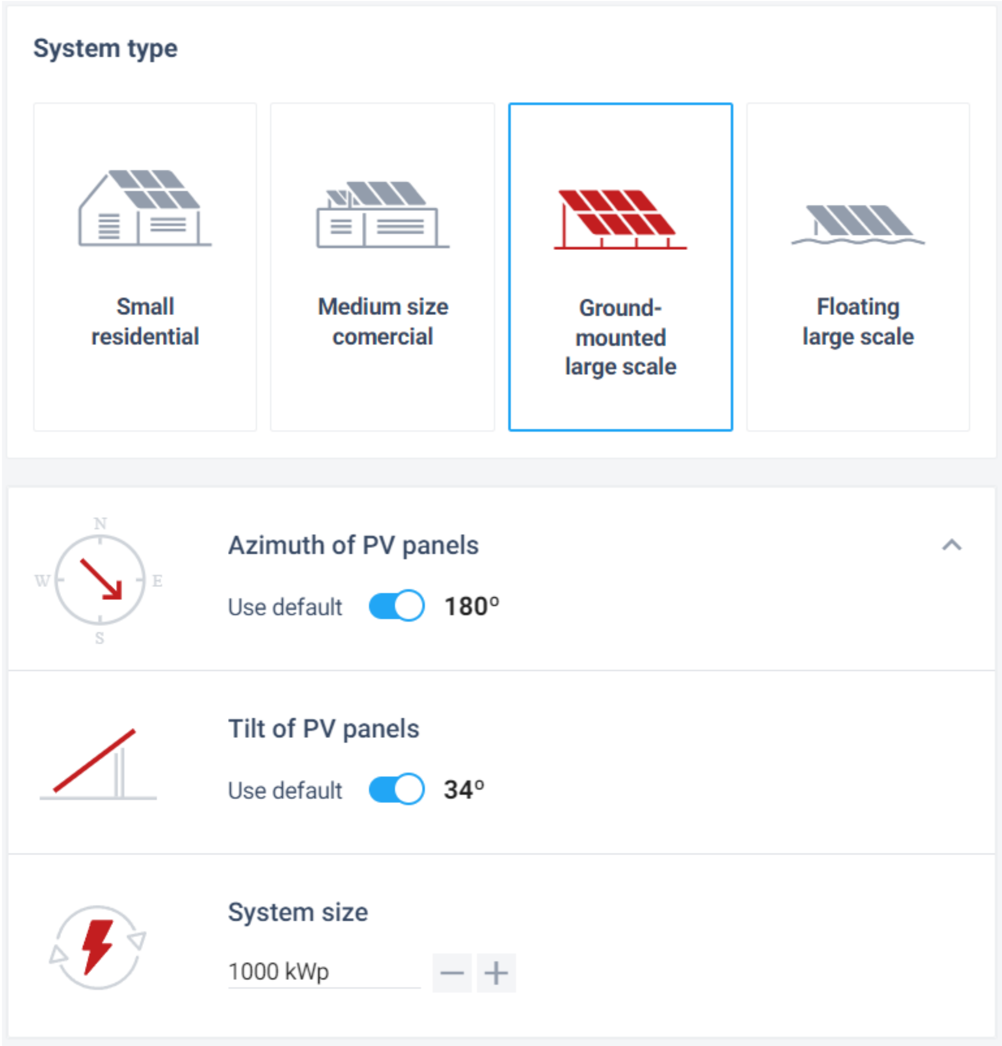


Figure 2.6 – System type selection

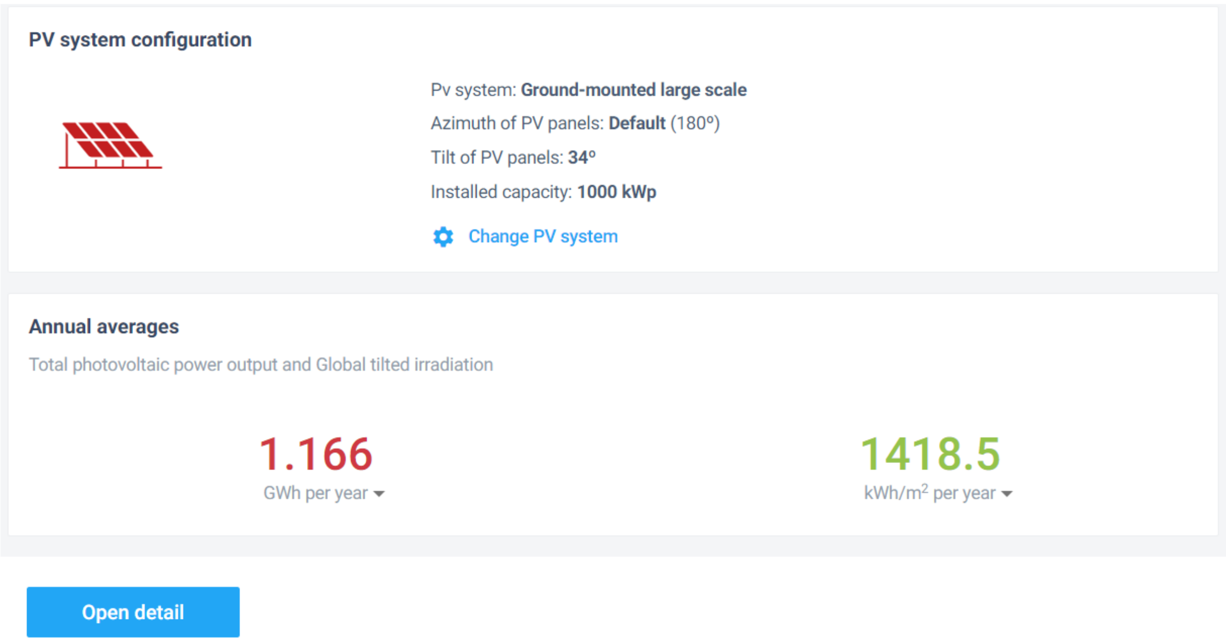


Figure 2.7 – PV system data (example for Kharkiv region 49°59'56", 036°15'34")

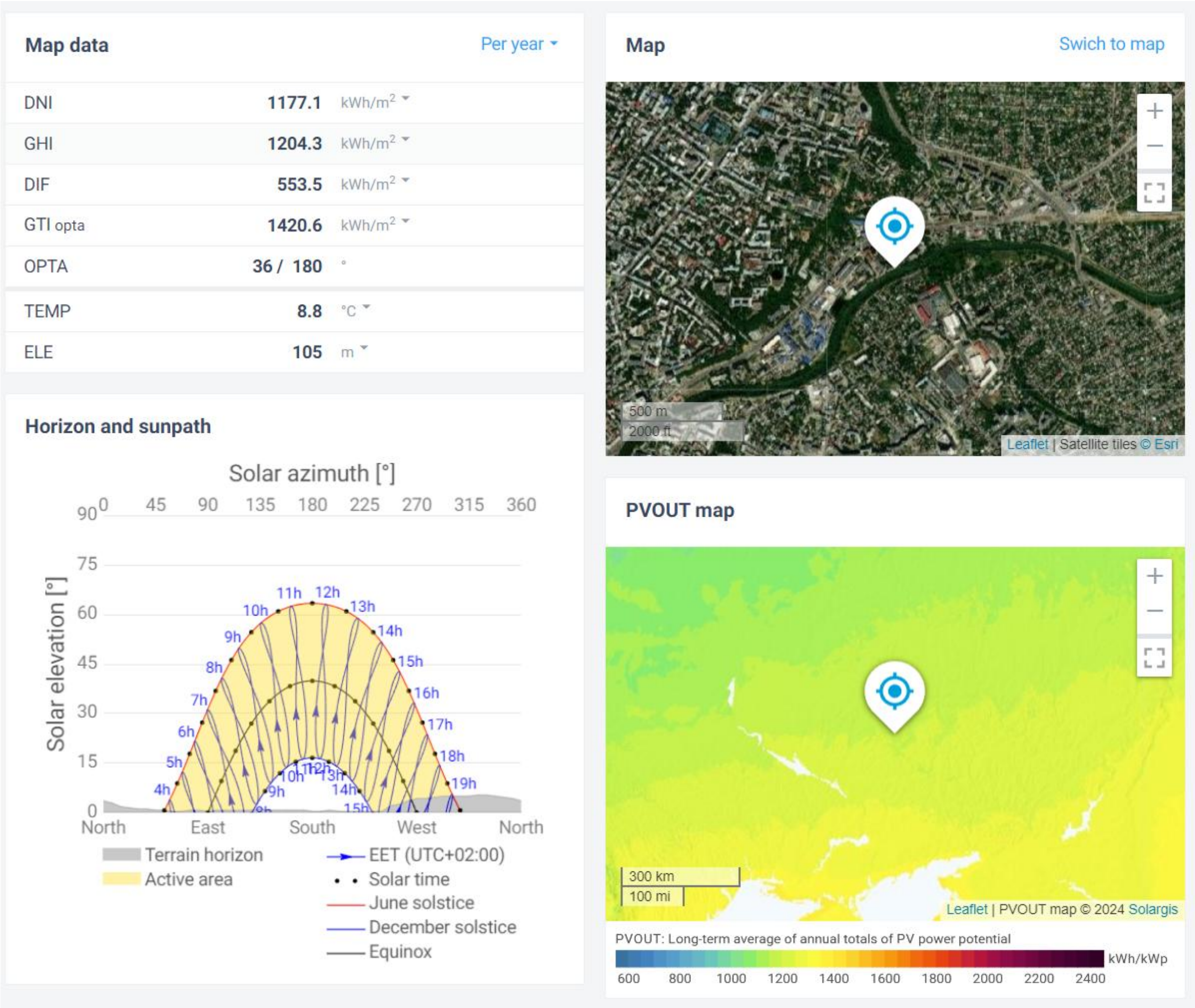
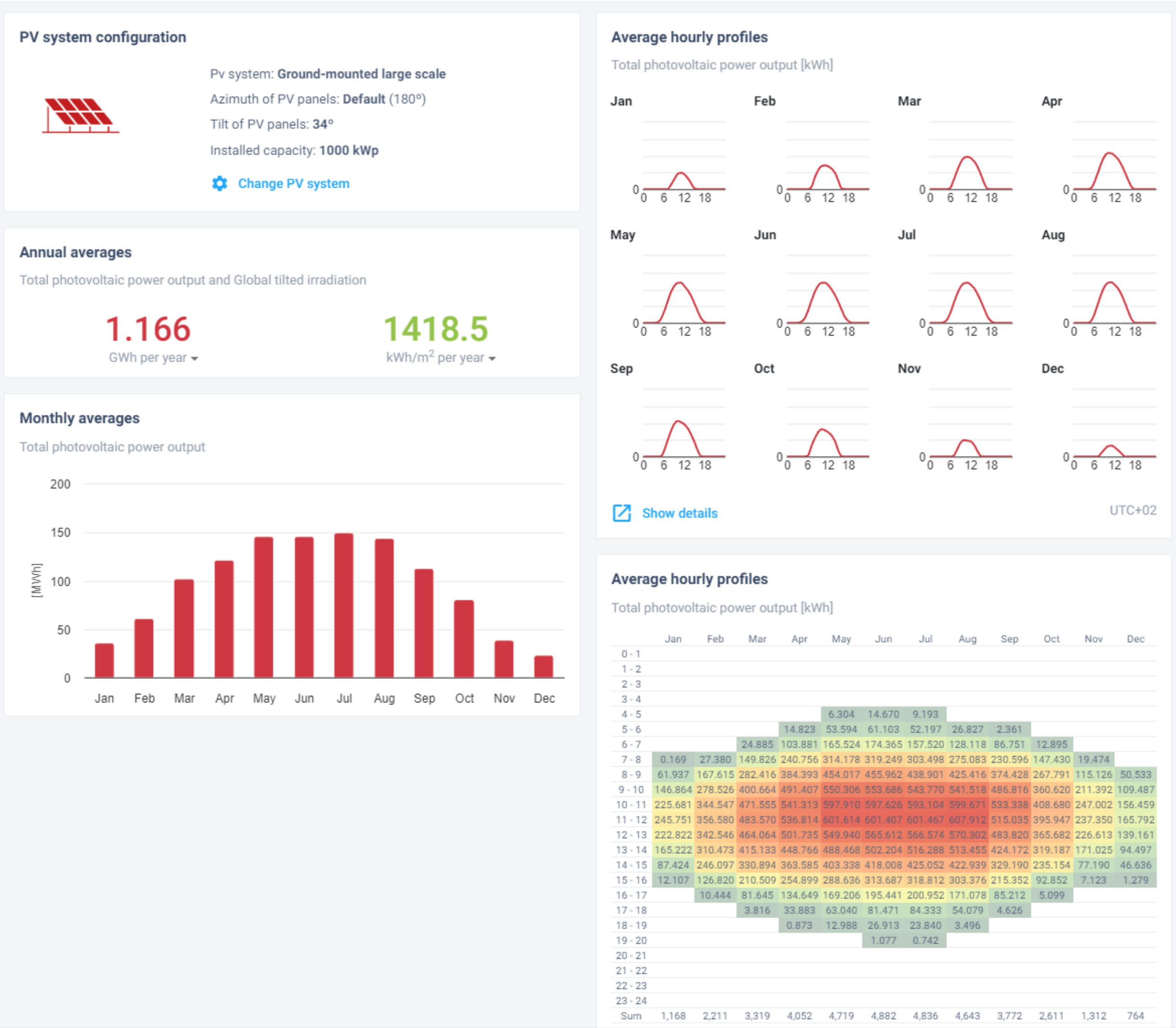


Figure 2.8 – Detailed PV system data: Map data; PV_OUT map; Horizon and sunpath (example for Kharkiv region 49°59'56", 036°15'34")



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0 - 1												
1 - 2												
2 - 3												
3 - 4												
4 - 5					6.304	14.670	9.193					
5 - 6				14.823	53.594	61.103	52.197	26.827	2.361			
6 - 7			24.885	103.881	165.524	174.365	157.520	128.118	86.751	12.895		
7 - 8	0.169	27.380	149.826	240.756	314.178	319.249	303.498	275.083	230.596	147.430	19.474	
8 - 9	61.937	167.615	282.416	384.393	454.017	455.962	438.901	425.416	374.428	267.791	115.126	50.533
9 - 10	146.864	278.526	400.664	491.407	550.306	553.686	543.770	541.518	486.816	360.620	211.392	109.487
10 - 11	225.681	344.547	471.555	541.313	597.910	597.626	593.104	599.671	533.338	408.680	247.002	156.459
11 - 12	245.751	356.580	483.570	536.814	601.614	601.407	601.467	607.912	515.035	395.947	237.350	165.792
12 - 13	222.822	342.546	464.064	501.735	549.940	565.612	566.574	570.302	483.820	365.682	226.613	139.161
13 - 14	165.222	310.473	415.133	448.766	488.468	502.204	516.288	513.455	424.172	319.187	171.025	94.497
14 - 15	87.424	246.097	330.894	363.585	403.338	418.008	425.052	422.939	329.190	235.154	77.190	46.636
15 - 16	12.107	126.820	210.509	254.899	288.636	313.687	318.812	303.376	215.352	92.852	7.123	1.279
16 - 17		10.444	81.645	134.649	169.206	195.441	200.952	171.078	85.212	5.099		
17 - 18			3.816	33.883	63.040	81.471	84.333	54.079	4.626			
18 - 19				0.873	12.988	26.913	23.840	3.496				
19 - 20						1.077	0.742					
20 - 21												
21 - 22												
22 - 23												
23 - 24												
Sum	1,168	2,211	3,319	4,052	4,719	4,882	4,836	4,643	3,772	2,611	1,312	764

Figure 2.9 – Detailed PV system data: Average hourly profiles in different forms; Monthly averages (example for Kharkiv region 49°59'56", 036°15'34")

Global Solar Atlas allows you to make screenshots with high resolution and use it for diploma thesis.

2.2.3 Downloadable maps and GIS data

The download section allows download of poster maps for presentation purposes. In addition, GIS data layers can be downloaded for advanced geospatial analysis using software such as QGIS and ArcGIS.

Solar resource and PV power potential maps and GIS data can be downloaded from this section. Maps and data are available for 200+ countries and regions. Please select a region or a country from the menu below. The maps and data have been prepared by Solargis for The World Bank. They are provided under CC BY 4.0 license with the following mandatory and binding addition (see Terms of use for more information).

GSA allows you to download data (Figure 2.10) of different countries of different size picture.

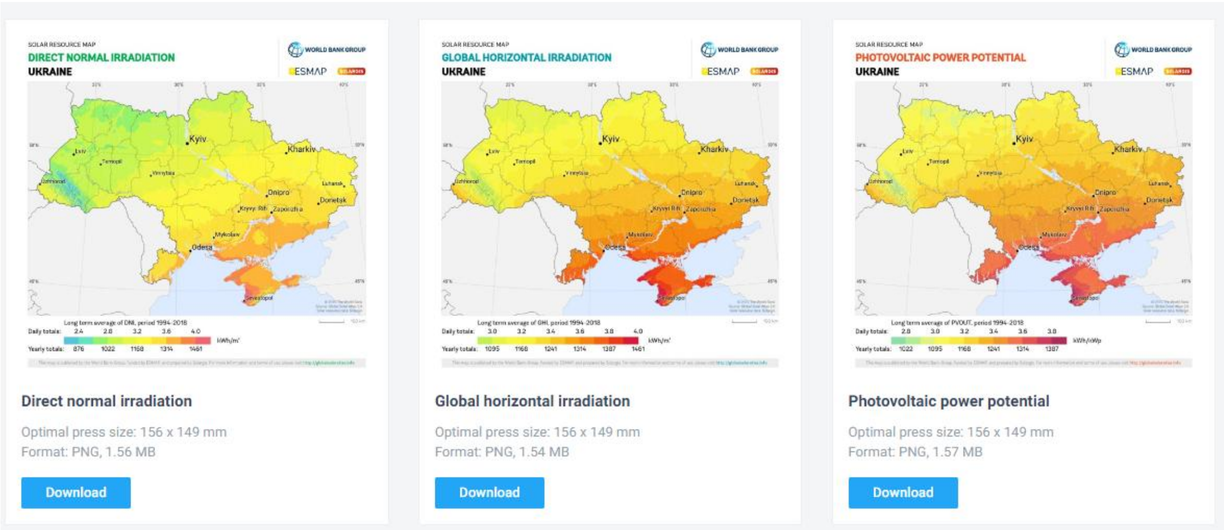


Figure 2.10 – Map and data downloads (for example was chosen Ukraine)

2.2.4 Country and regional solar potential statistics

Country-level snapshots of solar energy potential have been prepared to help policymakers and researchers to understand the theoretical and practical potential of solar energy for countries and regions of interest.

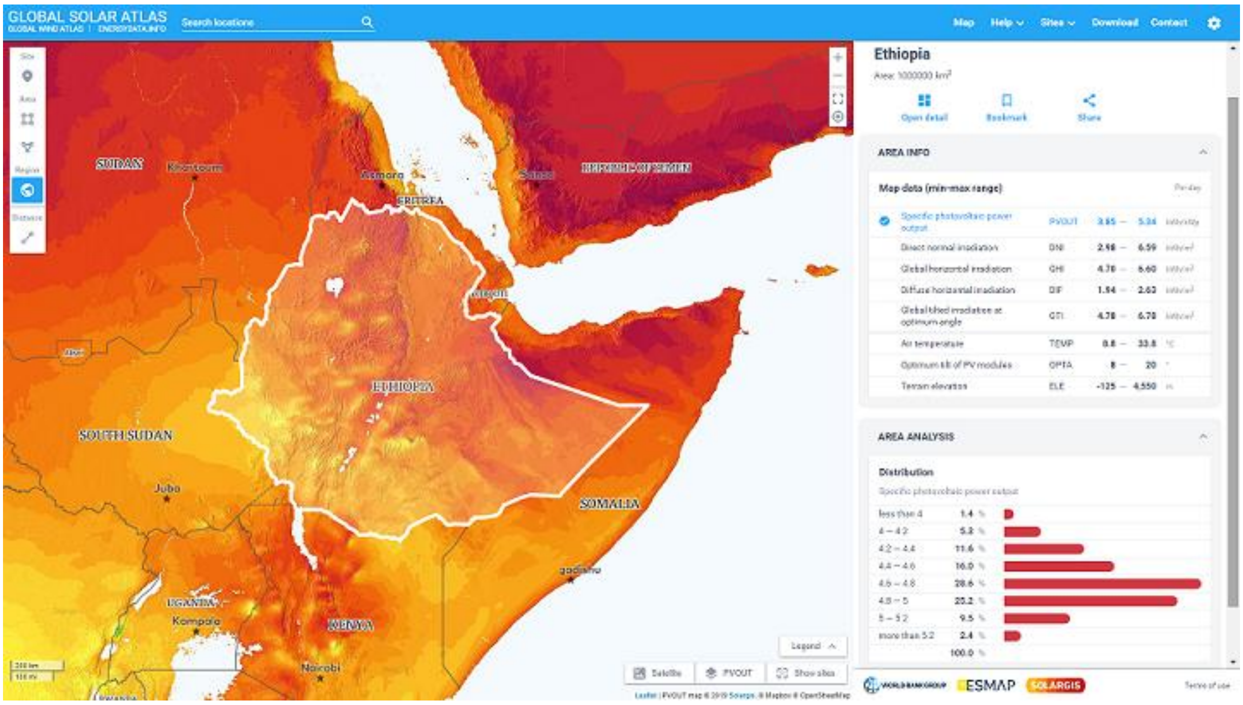


Figure 2.11 – Country and regional solar potential statistics (example on Ethiopia)

Limitation of Global Solar Atlas. The objective of the Global Solar Atlas is to provide reliable introductory-level data to help policymakers, researchers, and commercial solar companies take better decisions. For project-specific analysis of large power plants, the data available via the Global Solar Atlas is suitable only for preliminary analysis. The PV yield estimates do not account for many important factors that can impact potential yield of a photovoltaic power plant. For large power plants, it is recommended to work with more detailed yield estimation tools in order to obtain a precise estimate of energy yield.

Self-testing questions for Chapter 2

1) What is the primary aim of the Global Solar Atlas?
2) How can you access solar resource and PV power potential data using the Global Solar Atlas?
3) What are the three main models involved in the location-specific information provided by the Atlas?
4) How does the Global Solar Atlas help in understanding solar energy potential at country and regional levels?
5) What tools are available in the Global Solar Atlas for users to interact with solar resource data?
6) How does the PV energy yield calculator in the Global Solar Atlas assist in estimating energy yield for a custom-defined PV system?
7) What are the benefits of using the Global Solar Atlas for solar power plant calculations?
8) What factors are considered in the solar radiation model used by the Global Solar Atlas?
9) How does the PV power simulation model in the Global Solar Atlas account for external factors affecting photovoltaic system performance?
10) What types of PV system configurations can be selected for electricity calculation in the Global Solar Atlas?

3 CONFIGURATION OF SOLAR PHOTOVOLTAIC POWER PLANT ON DC SIDE

3.1 Irradiance

As a function of the irradiance incident on the PV module, its characteristic IV curve changes as shown in Figure 3.1.

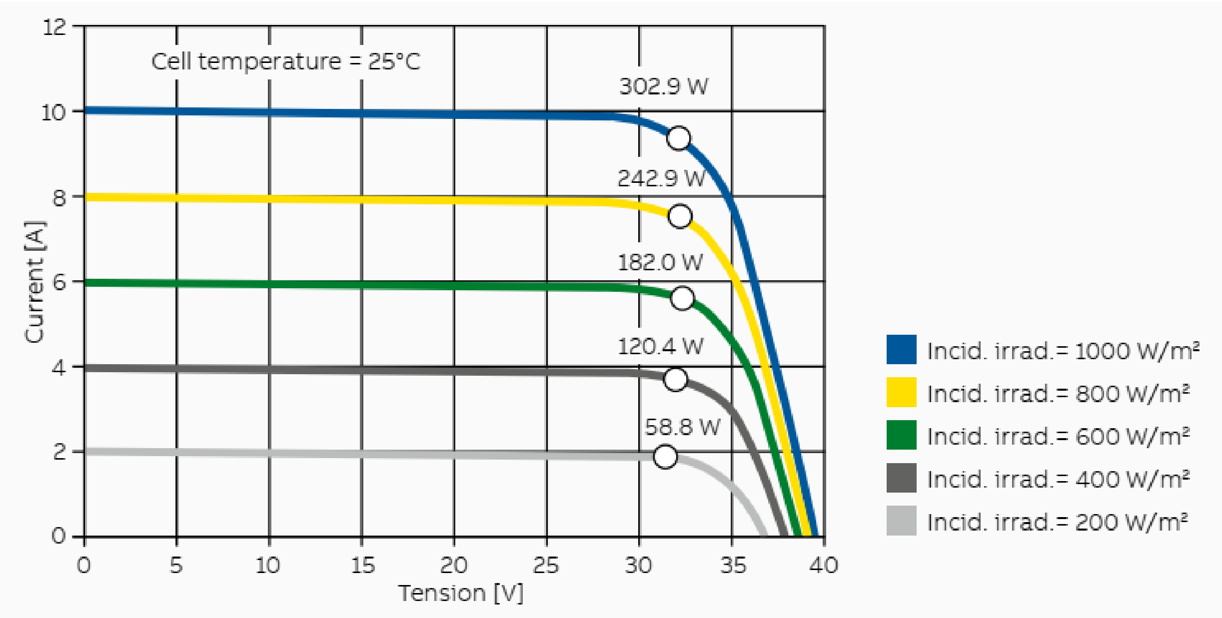


Figure 3.1 – Characteristics IV curve of a 60 monocrystalline 6-inch cells rated 300W at STC conditions

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

3.2 Temperature of the modules

Contrary to the previous case, when the temperature of the PV modules increases, the current produced remains practically unchanged, whereas the voltage decreases and with it there is a reduction in the performances of the PV module in terms of produced electric power as shown in Figure 3.2.

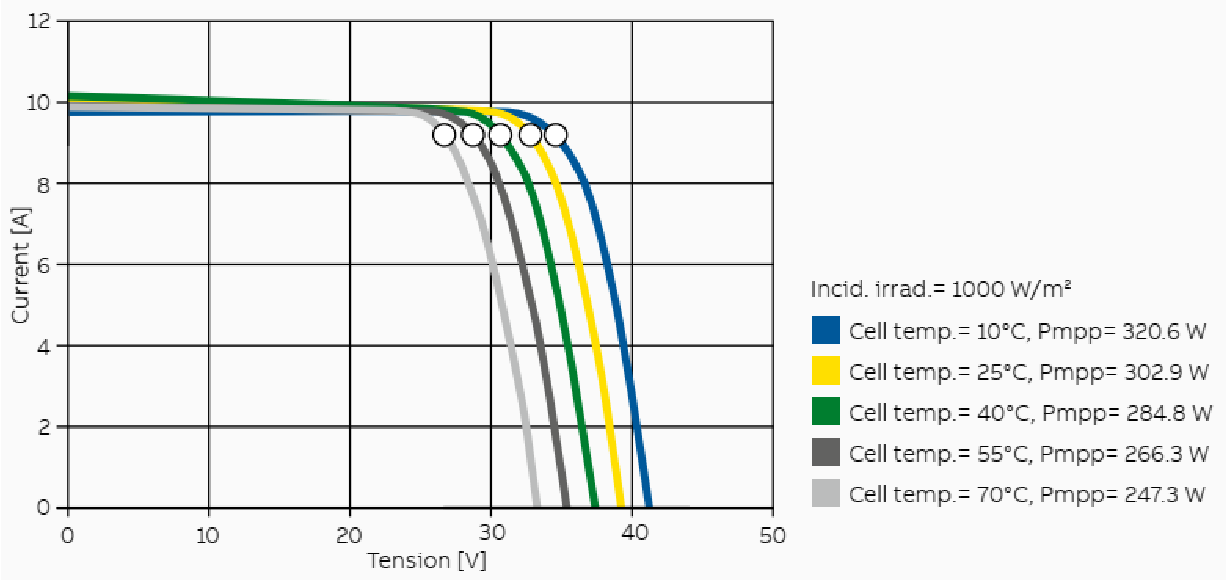


Figure 3.2 – Characteristics IV curve of a 60 monocrystalline 6-inch cells rated 300W at STC conditions

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

$$V_{OC}(T) = V_{OC\ STC} - \left[\beta' \cdot \left(25 - T_{cell}\right)\right] \tag{3.1}$$

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

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

3.3 Centralized distribution

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

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

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

3.4 String and central inverters configurations

3.4.1 Inverter size selection.

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

The inverter efficiency depends on its input DC power generated from the PV array, which depends on solar radiation and PV-cell temperature. The efficiency curve of PV inverter shows the relation of inverter efficiency with its output power as shown in Figure 3.3. It can be observed that, the efficiency reaches its maximum value when the inverter delivers about 40% of its nominal power. The efficiency also depends on the input voltage VPV. Therefore Figure 3.3 illustrates the efficiency at different input voltages of 6kW single phase inverter, and on Figure 3.4 the efficiency of powerful inverter ULTRA 780 to 1560 kW.

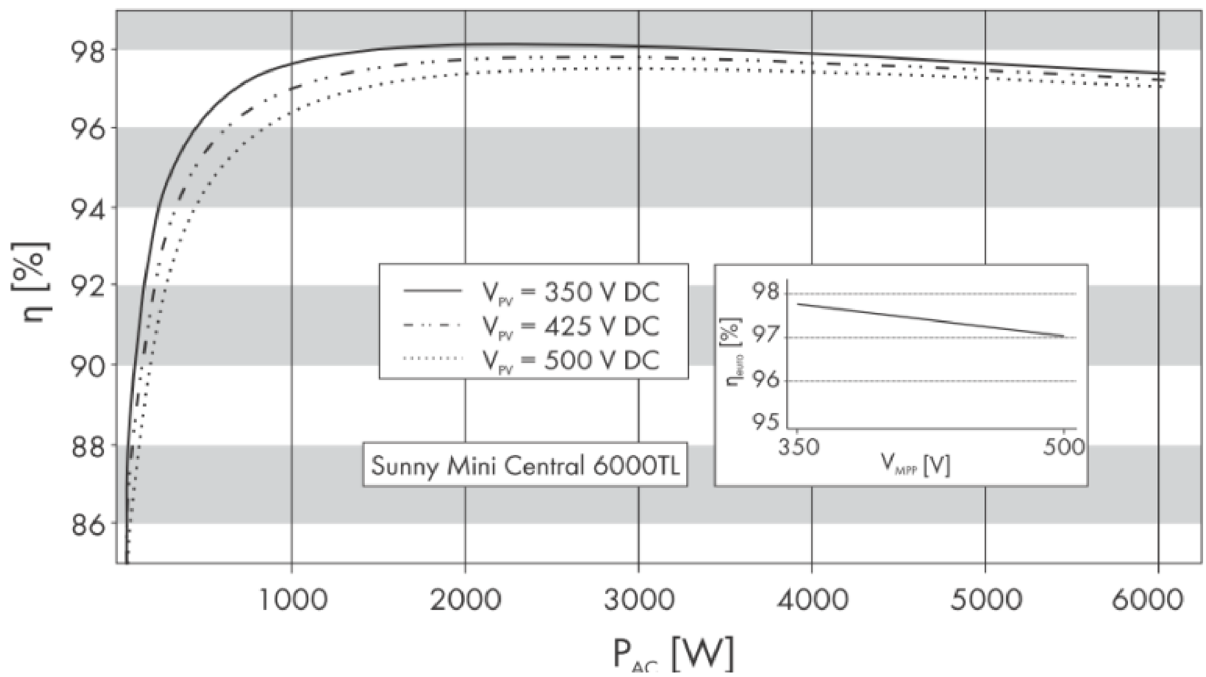


Figure 3.3 – The efficiency curve of 6kW single phase inverter

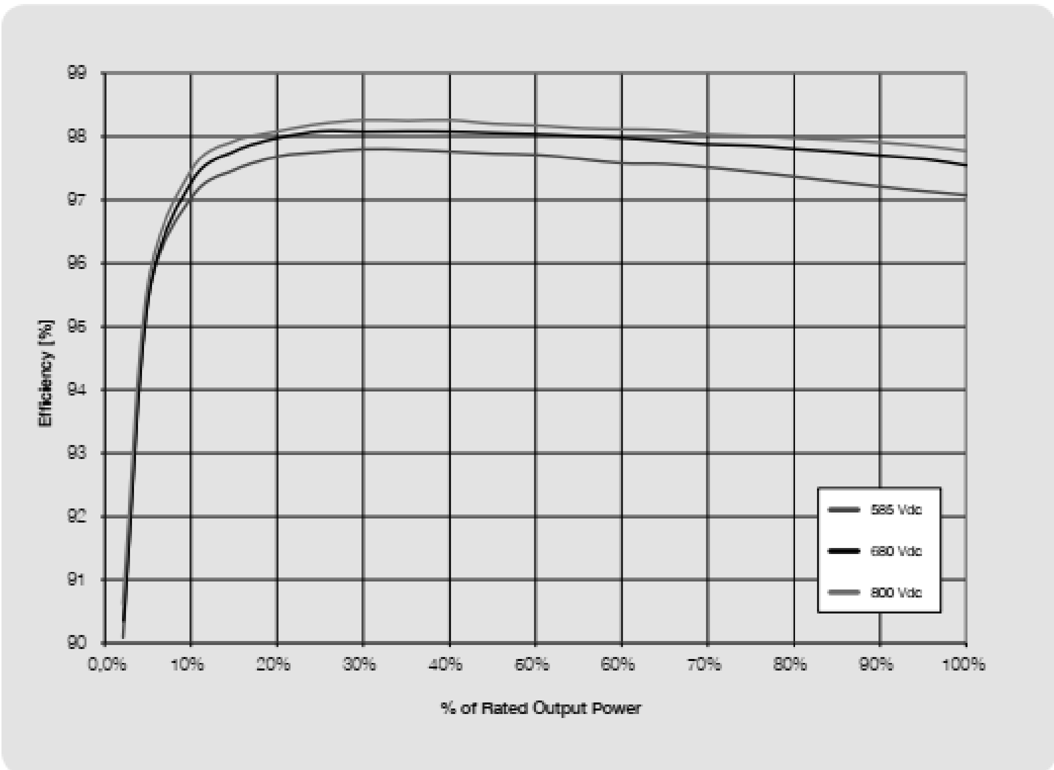


Figure 3.4 – Efficiency curves of ULTRA 780 to 1560 kW

At Appendix B, paragraph B.1shown datasheet of different invertors.

3.4.2 Determining the PV module max V_{oc}

At Appendix B, paragraph B.2 shown datasheet of different PV pannels.

According to IEC 60364-7-712. As already introduced in the paragraph 3.2 the variation of open circuit voltage V_{oc} of a PV module is a function of the operating temperature of the cells. The open circuit voltage V_{oc} is inversely proportional to the cell temperature and then it is highest at lower cell temperature.

The maximum open circuit voltage $V_{oc\ MAX}$ can be calculated using the following data:

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

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

$$V_{OC\ MAX} = V_{OC\ STC}\left[1 + \frac{\beta}{100}\cdot\left(T_{\min} - 25\right)\right] \tag{3.2}$$

$$V_{OC\ MAX} = V_{OC\ STC} + \beta'\cdot\left(T_{\min} - 25\right) \tag{3.3}$$

where $T_{\min}$ – assumed equal to the lowest temperature that can be expected at the PV installation location, can be measured in *°C* (by Celcium) or *K* (by Kelvin);

$V_{OC\ STC}$ – the PV module open circuit voltage at standard test conditions, *V*;

β – the variation coefficient of the voltage according to temperature and depends on the typology of PV module; it is measured in, %/*°C* or %/*K*;

β' – is the variation coefficient of the voltage according to temperature and depends on the typology of PV module; it is measured in, *mV/°C* or *mV/K*.

For some kind of PV modules, electrical characteristics, during the first weeks of operation, are higher than the characteristics indicated in the name plate of the PV module: this phenomenon shall be considered in the calculation of $V_{OC\ MAX}$. Furthermore, the electrical characteristics of other type of PV modules fall down during the life time of the PV modules for degradation mechanism (LID, LETID, PID): this phenomenon shall be considered in the calculation of $V_{OC\ MAX}$.

3.4.3 Determining the PV module min V_{MPP}

On the basis of the above, the minimum MPP voltage V_{MPP} min can be calculated using the following data:

- maximum temperature that can be expected at the PV installation location;
- PV module MPP voltage at STC condition $V_{MPP\ STC}$;
- PV module temperature coefficient.

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

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

$$V_{MPP\ \min} = V_{MPP\ STC}\left[1 + \frac{\beta}{100}\cdot\left(T_{cell} - 25\right)\right] \quad (3.4)$$

$$V_{MPP\ \min} = V_{MPP\ STC} + \beta'\cdot\left(T_{cell} - 25\right) \quad (3.5)$$

where T_{cell} – the maximum cell temperature that can be expected at the PV installation location, °*C* or *K*;

$V_{MPP\ STC}$ – the PV module MPP voltage at standard test conditions, *V*;

β – the variation coefficient of the voltage according to temperature and depends on the typology of PV module; it is measured in, *%/°C* or *%/K*;

β' – is the variation coefficient of the voltage according to temperature and depends on the typology of PV module; it is measured in, *mV/°C* or *mV/K*.

3.4.4 Determining the Maximum Number of PV Modules per String

The maximum number of PV modules connected in series that could be connected to the inverter is defined based on the assumption that the string voltage is always below the maximum input voltage of the inverter. In case string voltage exceeds the input voltage of the inverter, damage to the inverter could occur by overvoltage. Must be round down.

$$N_{MAX\ Module} \leq \frac{V_{MAX\ Inverter}}{V_{OC\ MAX\ Module}} \tag{3.6}$$

where $N_{MAX\ Module}$ – the maximum number of PV modules connected in series per string;

$V_{MAX\ Inverter}$ – the maximum input voltage of inverter, V;

$V_{OC\ MAX\ Module}$ – the PV module maximum V_{oc}, V.

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

$$V_{MAX\ system} \geq N_{MAX\ Module} \cdot V_{OC\ MAX\ Module} \tag{3.7}$$

where $V_{MAX\ system}$ – the maximum system voltage of all components of the PV system.

3.4.5 Determining the PV string max V_{oc}

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

$$V_{OC\ MAX\ String} = N_{MAX\ Module} \cdot V_{OC\ MAX\ Module} \tag{3.8}$$

3.4.6 Determining the Minimum Number of PV Modules per String

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

$$N_{\min\ Module} \geq \frac{V_{\min\ MPPT\ Inverter}}{V_{MPP\ \min\ Module}} \tag{3.9}$$

where $N_{\min\ Module}$ – the minimum number of PV modules connected in series per string;

$V_{\min\ MPPT\ Inverter}$ – the minimum MPP voltage of the inverter, V;

$V_{MPP\ \min\ Module}$ – the PV module minimum $V_{MPP,}$ V.

3.4.7 Number of PV Modules per String

The number of PV modules per string $\left(N_{Module}\right)$ must, as shown at formulae (3.10):

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

$$N_{Min\ Module} \leq N_{Module} \leq N_{Max\ Module} \tag{3.10}$$

3.5 Determining the Maximum PV Module Current

As already introduced in the paragraph 3.2 the variation of short-circuit current I_{sc} of a PV module is a function of the operating temperature of the cells. The short-circuit current I_{sc} is proportional to the cell temperature and then it is highest at maximum cell temperature. On the basis of the above, the maximum PV module short-circuit current $I_{sc\ MAX\ Module}$ can be calculated using the following data:

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

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

$$I_{SC\ MAX\ Module} = I_{SC\ STC}\left[1-\frac{\alpha}{100}\cdot\left(25-T_{cell}\right)\right] \qquad (3.11)$$

$$I_{SC\ MAX\ Module} = I_{SC\ STC} - \alpha'\cdot\left(25-T_{cell}\right) \qquad (3.12)$$

where T_{cell} – the highest temperature that can be expected at the PV installation location, °*C* or *K*;

$I_{SC\ STC}$ – the PV module short-circuit current at standard test conditions, *A*;

α – the variation coefficient of the current according to temperature and depends on the typology of PV module; it is measured in, *%/°C* or *%/K*;

α' – the variation coefficient of the current according to temperature and depends on the typology of PV module; it is measured in, *mA/°C* or*mA/K*.

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

$$I_{SC\ MAX\ Module} = K\cdot I_{SC\ STC} \qquad (3.13)$$

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

3.5.1 Determining the Maximum PV string Current

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

$$I_{SC\ MAX\ Module} = I_{SC\ MAX\ String} \qquad (3.14)$$

3.5.2 Determining the String Number

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

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

$$N_{MAX\ String} \leq \frac{I_{MAX\ input}}{I_{SC\ MAX\ String}} \tag{3.15}$$

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

$$N_{MAX\ String} \leq \frac{I_{MAX\ inverter}}{I_{SC\ MAX\ String}} \tag{3.16}$$

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

3.6 Array physical configuration

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

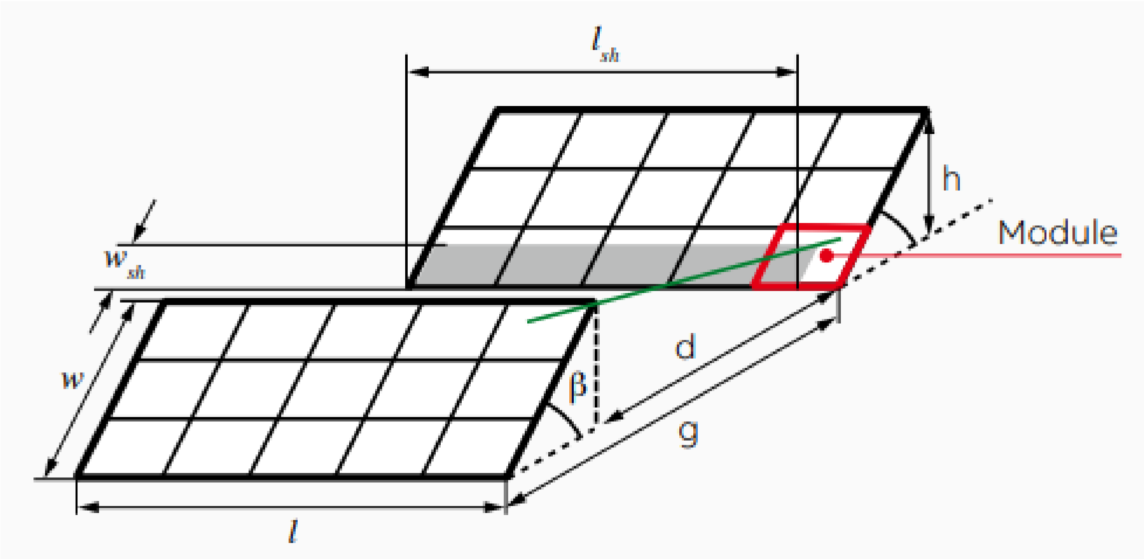


Figure 3.5 – Distance between neighbouring rows – row spacing

The width of the panel is:

$$w = n \cdot h_{module} \tag{3.17}$$

where n – number of modules;

h_{module} – width of the module, *mm*.

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

$$h = w \cdot \sin \beta \tag{3.18}$$

where β – installation tilt of panels, °.

The height difference strictly depends from the PV module positioning in the panel. Another parameter necessary to calculate the row spacing is the sun elevation. In order to avoid shading between 10:00 AM and 2:00 PM on December 21 (winter solstice) at a module inclination angle, the sun elevation could be identified by the sun path charts in Cartesian coordinates (Figure 3.6).

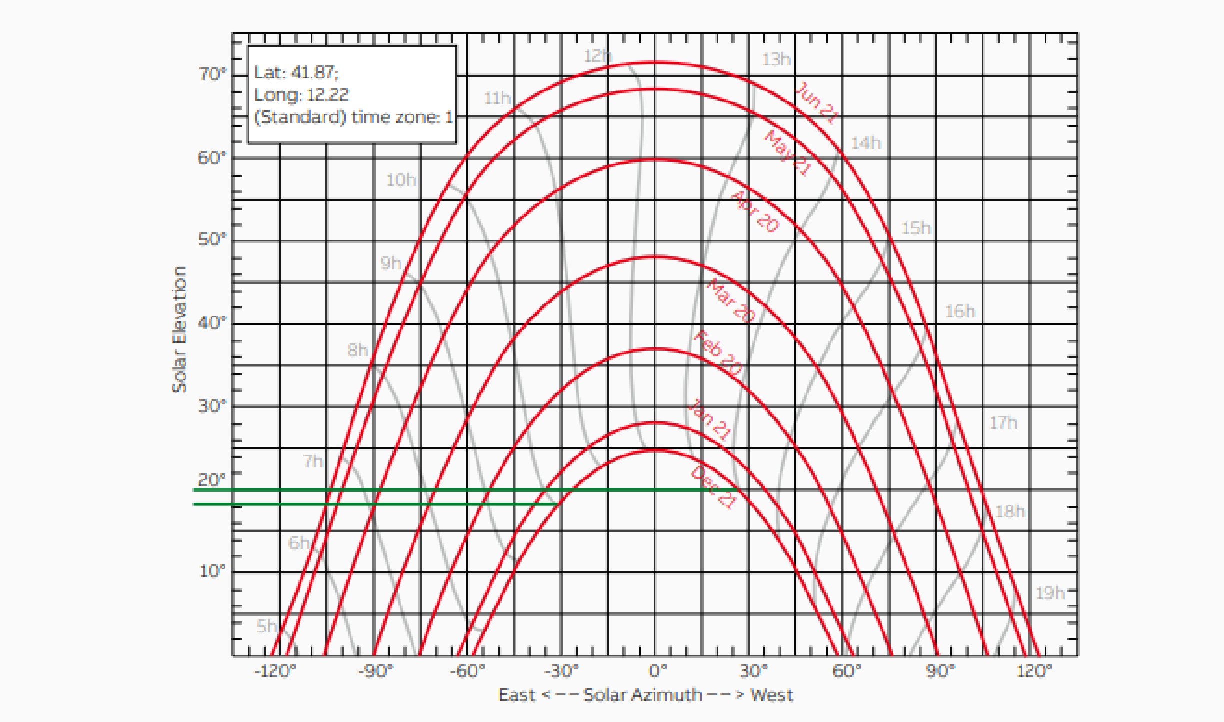


Figure 3.6 – Sun path in latitude 41.871730 and latitude 12.217600

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

$$d = \frac{h}{\tan\theta} \tag{3.19}$$

The row width is:

$$g = d + w \cdot \cos\beta \tag{3.20}$$

3.7 Definitive inverter layout

In order to optimize the cabling of the modules, is a best practice to consider the array physical configurations, paragraph 1.4 (panel configuration), in the selection of string dimensions.

The inverters available on the market have a rated power up to about 10 kW single-phase and about 550 kW three-phase.

In small-size plants up to 6 kW with single-phase connection to the *LV* network, a single inverter is usually installed, whereas in plants over 6 kW with three-phase connection to the *LV* or *MV* grid, more inverters are usually installed.

In small/medium-size plants it is usually preferred the solution with more single-phase inverters equally distributed on the three phases, common neutral and with a single transformer for the separation from the public network (Figure 3.7). Instead, for medium- and large-size plants it is usually convenient to have a structure with few three-phase inverters to which several strings are connected in parallel on the DC side in the PV string combiner boxes (Figure 3.8).

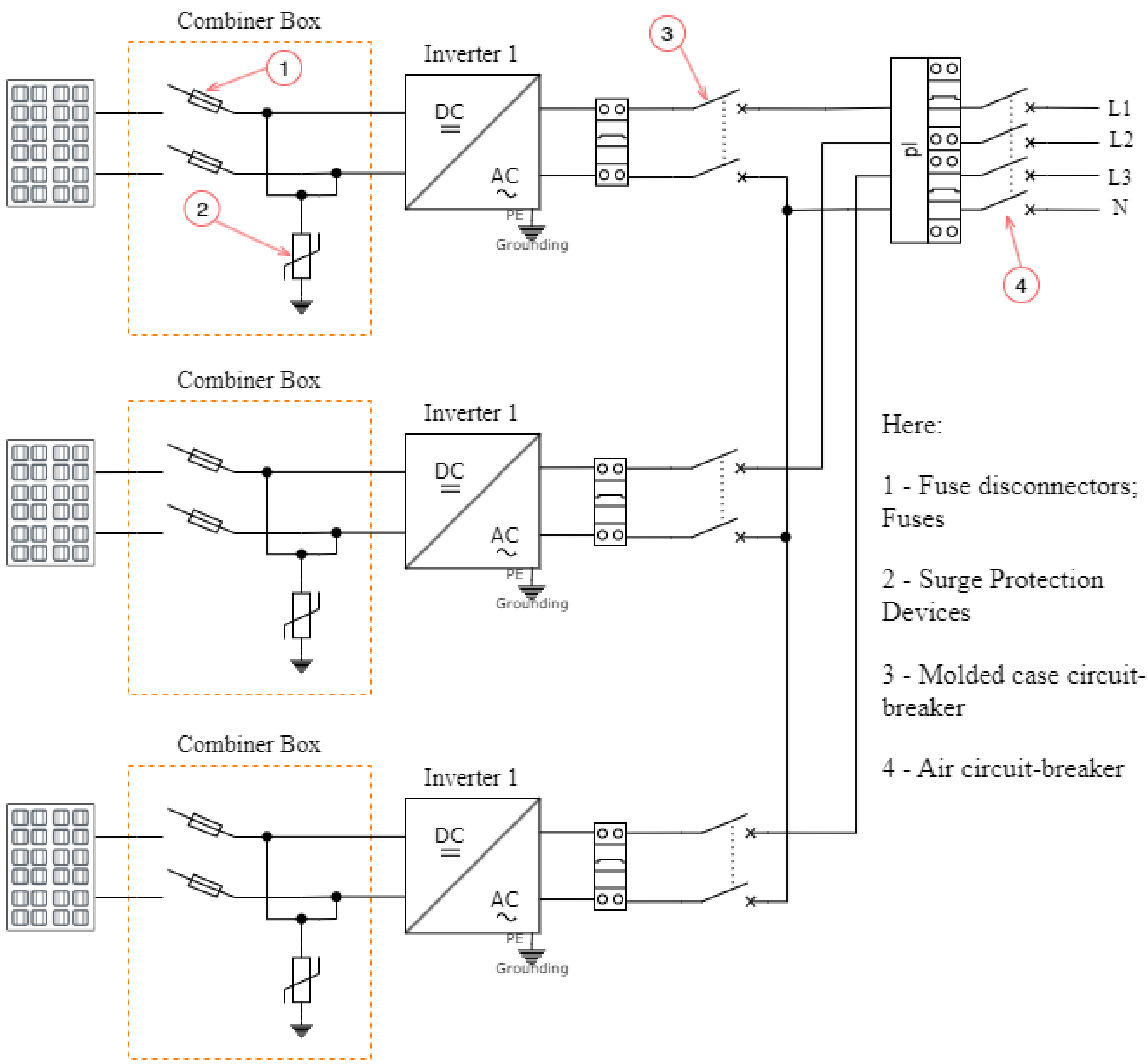


Figure 3.7 – Structure of medium-size PV plant

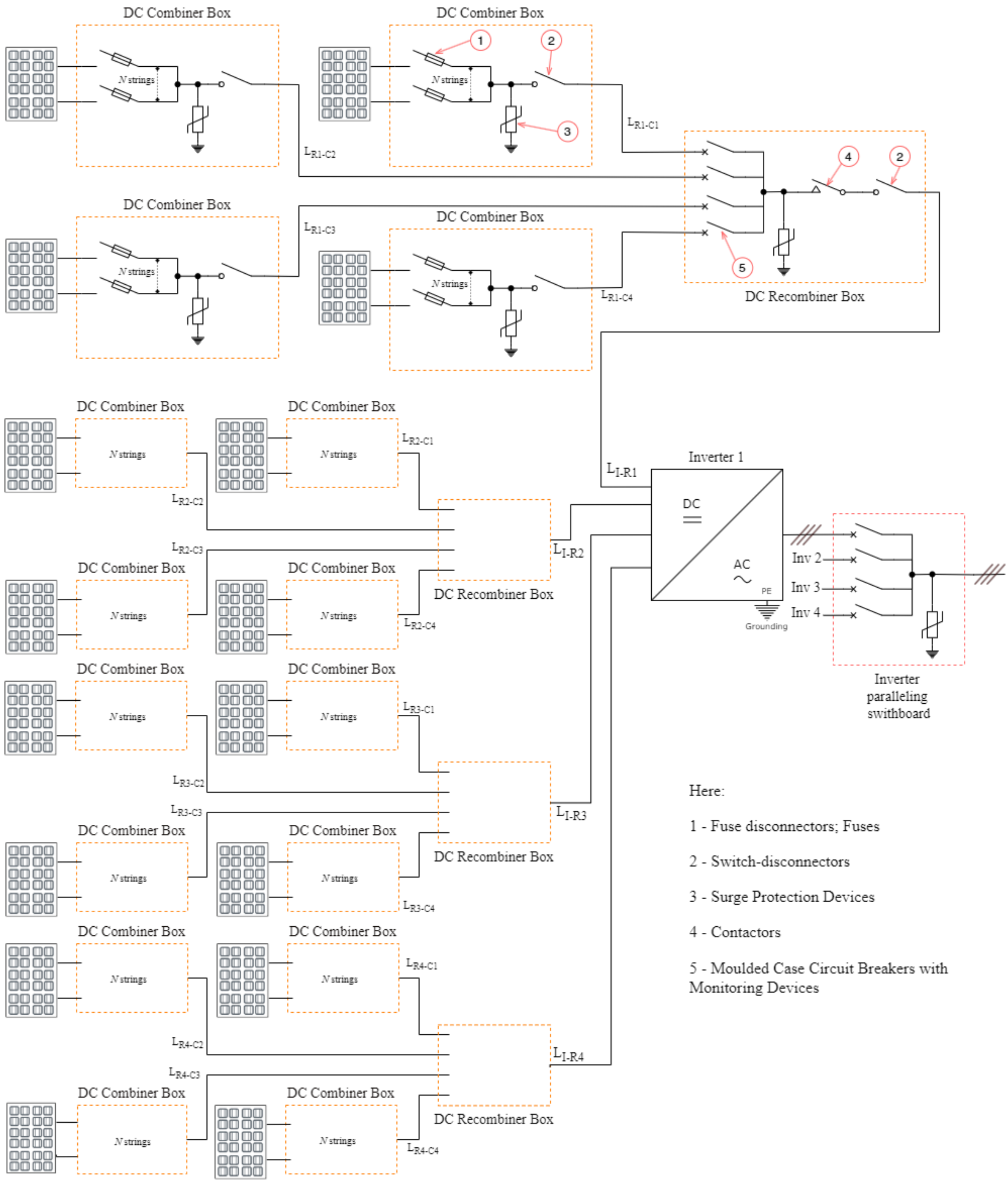


Figure 3.8 – Structure of large-size PV plant

The disconnection of the inverter must be possible both on the DC side as well as on the AC side so that maintenance is allowed by excluding both the supply sources, that is PV generator and grid. Besides, as shown in Figure 3.8, it is advisable to install a disconnecting device on each string, so that verification and maintenance operations on each string are possible without putting out of service the other parts of the plant.

We must evenly divide PV field into N_{subsys} sub-systems, where each sub-system is equipped with 1 inverter.

3.8 DC Combiner boxes

Combiner: Also called junction box or combiner box. Through this combiner, individual DC circuits from photovoltaic modules are combined into a single output. A combiner might include disconnect devices, overcurrent devices and remote monitoring devices.

As shown in paragraph 3.7, the connection of modules in series is made on the modules themselves, while the parallel connection of the strings is made inside combiner boxes that accommodate, along with the interconnection systems, also the overcurrent protection devices, disconnectors and surge protection devices. The combiner boxes form subsystems that can be standardized according to the number of strings, voltage and rated current.

Each one of the large-scale sub-systems is composed by N_{string} string of $N_{modules}$ PV modules. The N_{string} strings are connected in combiner boxes. After that, according to number of inverter input, combiner boxes connected into recombiner boxes.

In the combiner box selection (Table 3.1) should be considered:

- The maximum system voltage of all components shall be compatible with the maximum input voltage of the PV field. The maximum DC system voltage shall be equal to $U_{MAX(DC)}$;
- The disconnector conventional free-air thermal current (I_{th}) shall be compatible with the maximum current of the connected strings, then:

$$I_{th} > N_{string} \cdot I_{SC\ MAX\ string} \quad (3.21)$$

The fuses installed in the fuse holders$_{40}$ shall be *gPV* fuses with a maximum current I_n:

$$1.5 \cdot I_{SC} < I_n < 2.4 \cdot I_{SC} \quad (3.22)$$

$$I_n < I_{rev\ module} \quad (3.23)$$

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

I_{SC} – PV modules short-circuit current.

Table 3.1 – Technical data for Combiner boxes 1000*V* and 1500*V*

Maximum Voltage, *V*	1000											
Number of DC Input (+ & -, optional)	4	6	8	10	12	14	16	18	20	24	28	32
Fuse Max Size, *A*	20											

Maximum Voltage, *V*	1500					
Number of DC Input (+ & -, optional)	16	18	20	24	28	32
Fuse Max Size, *A*	20					

3.9 DC Recombiner boxes

If the number of combiner boxes is greater than the number of inverter inputs, then you need to use recombiner boxes.

$$N_{combiner\,boxes} > N_{inverter\,inputs} \tag{3.24}$$

The parallel connection of the cables that come from the combiner boxes is made inside recombiner boxes (Table 3.1) that accommodate, along with the interconnection systems, also the overcurrent protection devices, disconnectors and surge protection devices.

Moulded case circuit-breaker to obtain overcurrent protection; the disconnector rated service current (I_n) shall be compatible with the maximum current of the connected strings.

$$1.25 \cdot S_{SA} \cdot I_{SC} < I_n < 2.4 \cdot S_A \cdot I_{SC} \tag{3.25}$$

where S_{SA} – the number of parallel-connected PV strings in the PV sub-array;
S_A – the total number of parallel-connected PV strings in the PV sub-array.

Switch disconnector: the disconnector conventional free-air thermal current (I_{th}) shall be compatible with the maximum current of the connected strings.

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

3.10 Grounding

All equipment must be grounded. The concept of earthing applied to a photovoltaic (PV) system may involve both the exposed conductive parts (e.g.

metal frame of the PV modules) as well as the live parts of the PV system (e.g. the cells).

In accordance with IEC 62548, the following options of earthing or bonding of parts of PV arrays could occur: Earthing for lighting protection; Equipotential bonding to avoid uneven potentials across an installation; Functional earthing of conductive non-current carrying parts: in this case, earthing or bonding of PV array exposed conductive parts (e.g. metal frame of the panels) shall be performed according to the flow chart requirements; to realize earthing in the field refer to IEC 62305-3. Functional earthing of a PV array pole: functionally earthed PV array architectures.

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

3.11 The diagram of DC part of Photovoltaic Power Plant

Figure 3.9 shows the single-line diagram of the DC side of a PV plant including its main electrical equipment. The main electrical equipment includes PV modules, inverters, connectors, combiner box (also called junction box), DC protections, DC switches, and DC cables.

The most important technical specifications that must be determined for the DC side equipment are as follows:

- PV modules technology;
- Inverter configuration;
- PV plant size;
- PV modules number.

In case of Large-Scale PV Power Plant, number of inverter input is not enough, so we need to use one more level of cable combining – recombiner box, as shown on Figure 3.10.

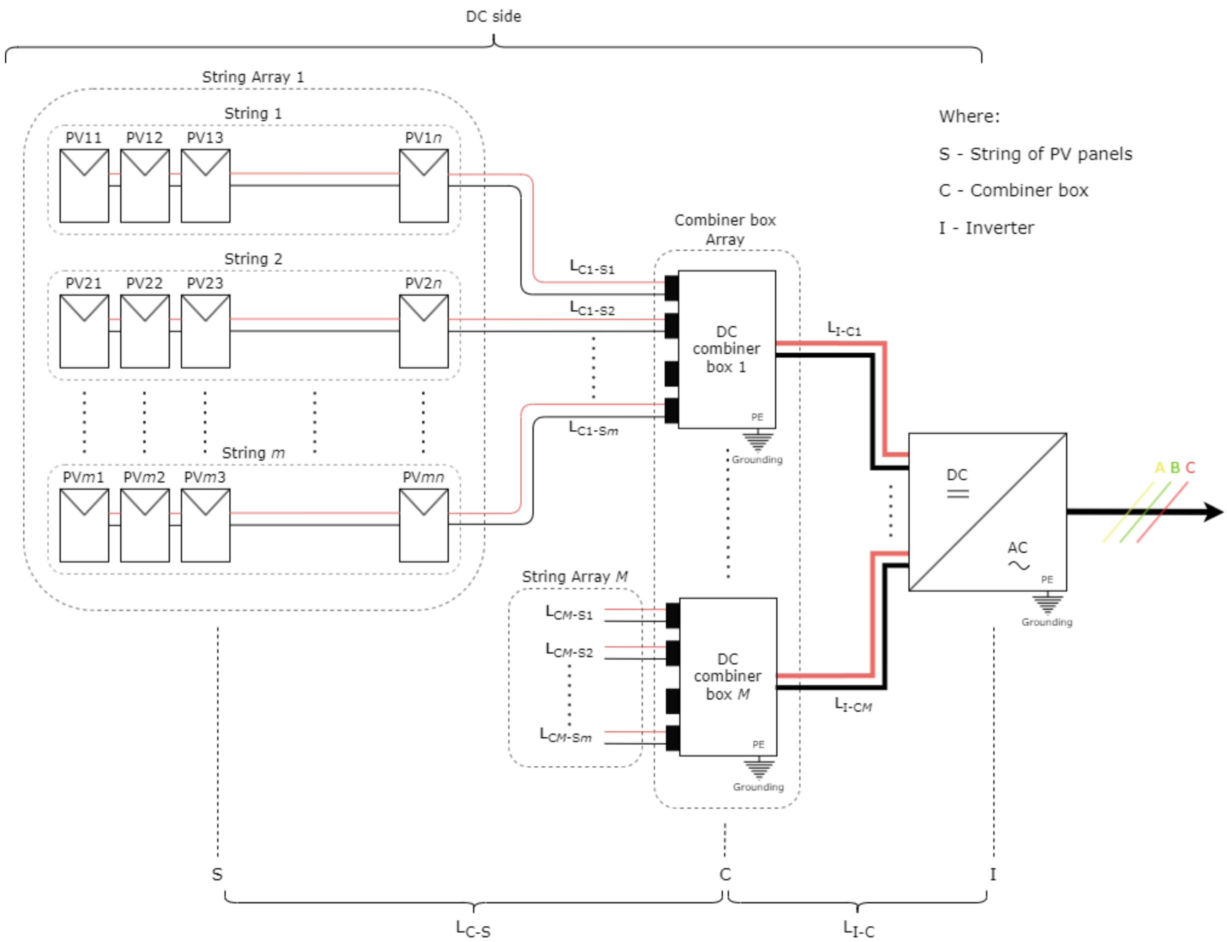


Figure 3.9 – Single-line diagram of DC side of a PV power plant

At Table 3.2 and Table 3.3 shown average length of cable connections of subsystems for different layout of PV Power Plant.

Table 3.2 – Average length between elements without recombiner box

Line	**Circuit length, m**
$L_{C\text{-}S}$	100
$L_{I\text{-}C}$	150

Figure 3.9 and Figure 3.10 is a structural scheme which is show compose of main elements of DC side of PV Power Plant.

Structural scheme consists of:

- Number of panels;
- Number of strings;
- Number combiner boxes;
- Number recombiner boxes, if needed;
- Inverter;
- Cable connections of all elements.

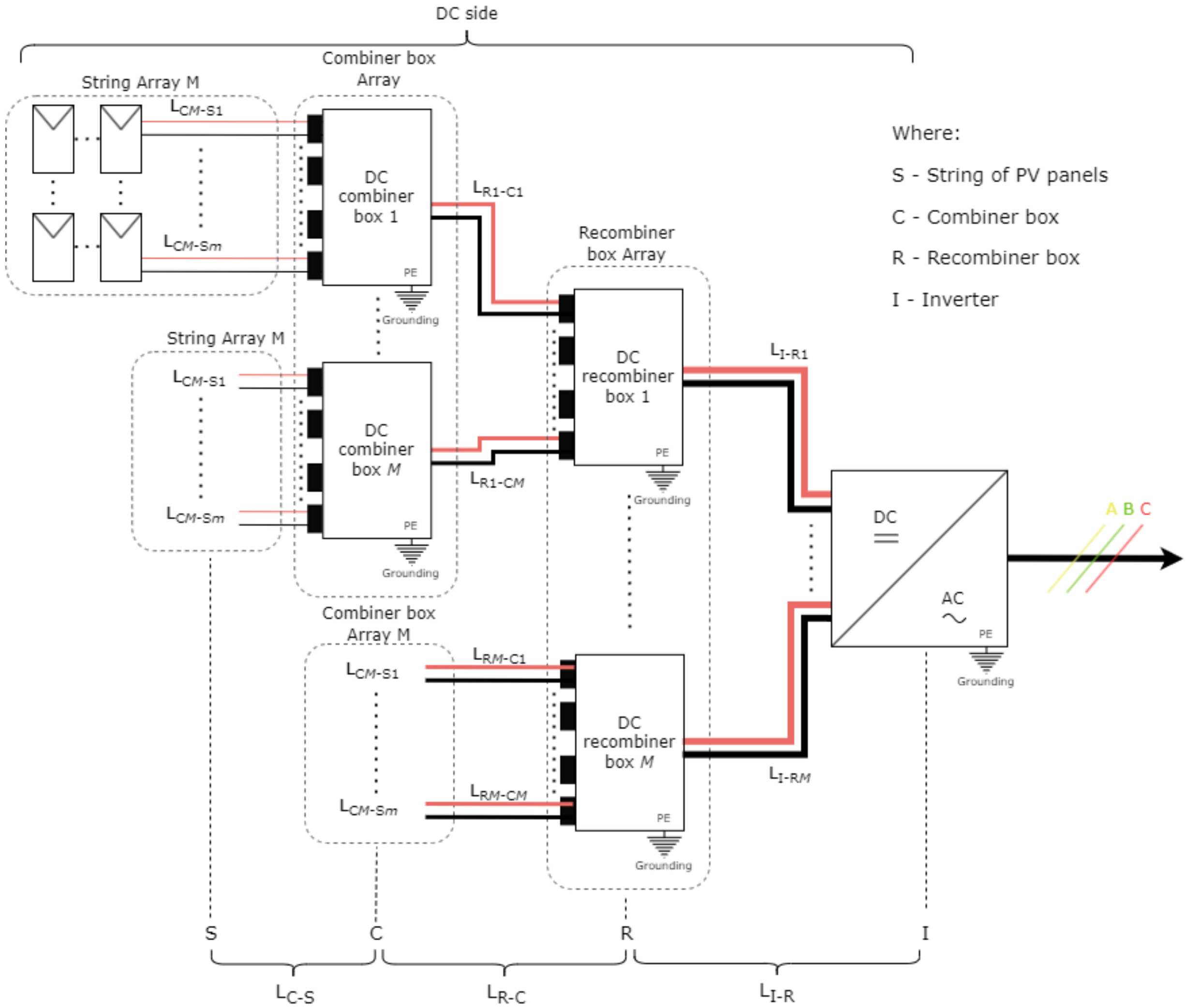


Figure 3.10 – Single-line diagram of DC side of a Large-Scale PV power plant

Table 3.3 – Average length between elements with recombiner box

Line	**Circuit length, m**
$L_{C\text{-}S}$	100
$L_{R\text{-}C}$	150
$L_{I\text{-}R}$	150

Self-testing questions for Chapter 3

1) What are the advantages of being able to disconnect the inverter on both the DC and AC sides in a PV plant for maintenance purposes?

2) Why is it advisable to install a disconnecting device on each string in a PV plant, as mentioned in the document?

3) In small/medium-size PV plants, what is the preferred solution for the distribution of single-phase inverters on the three phases?

4) For medium- and large-size PV plants, what is the typical structure in terms of inverters and connection of strings on the DC side?

5) According to IEC 62548, what are the different options for earthing or bonding parts of PV arrays?

6) What are the key differences between DC transmission and AC transmission in terms of conductors, cable cross-section, inductance, and voltage drop?

7) How does the elevation of the sun at different times of the day impact the row spacing and row width of PV panels?

8) What factors should be considered when selecting string dimensions for optimizing module cabling in a PV plant?

9) What is the typical rated power range for inverters available on the market for single-phase and three-phase connections in PV plants?

10) Which standard should be referred to for guidelines on earthing in the field for PV arrays according to the document?

4 EQUIPMENT SELECTION OF DC PART

4.1 Cables cross-sectional area and current carrying capacity

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

Selection the cross-sectional area of the conductor, chooses from Table 4.1 as closer to minimum possible cross-section:

$$S_{cross-section} \geq S_{\min} \quad (4.1)$$

where $S_{\min}$ – the minimal allowance cross-section of cable according to current and voltage drop.

$$S_{\min} = \frac{\rho \cdot L \cdot I_{section}}{\partial V_{\max}} \quad (4.2)$$

where L – length of the conductor of section, *m*;

ρ – specific resistance of the cable material, $\frac{\Omega \cdot mm^2}{m}$: 0.0175 – for copper; 0.0281 – for aluminium;

$I_{section}$ – nominal current rating, *A*;

$\partial V_{\max}$ – maximum allowed voltage drops, *V*.

$$\partial V_{\max} = \frac{\alpha}{100} \cdot V_{OC\ MAX\ string} \quad (4.3)$$

where α – percentage of allowance voltage drop, should not exceed 1÷3%;

$V_{OC\ MAX\ string}$ – maximum open circuit voltage with voltage multiplication factor, paragraph 0.

Table 4.1 – Aluminium PV cable 1500 *V*, according to IEC 60502-1

Type	Cross-section, mm^2	The continuous current-carrying capacity I_z	
		Open air current, *A*	On surface current, *A*
Al 1,5	1.5	30	29
Al 2,5	2.5	41	39
Al 4	4	55	52
Al 6	6	70	67
Al 10	10	98	93
Al 16	16	102	95
Al 25	25	121	98
Al 35	35	150	117
Al 50	50	184	139
Al 70	70	237	170
Al 95	95	289	204
Al 120	120	337	233
Al 150	150	389	261
Al 185	185	447	296
Al 240	240	530	343
Al 300	300	613	386
Al 400	400	740	444
Al 500	500	856	510
Al 630	630	996	588

4.1.1 PV modules string cables

The voltage rating of a cable refers to the maximum voltage to which it may be connected. If the voltage rating is exceeded, the insulation between cable cores, or between a cable core and earth, may break down and cause a short-circuit or a fire. The cables voltage rating shall be chosen according to the maximum open circuit voltage $V_{OC\,MAX\,string}$ (formulae (3.8)) of the strings. According to the number of PV Modules per string the maximum open circuit voltage ($V_{OC\,MAX\,string}$) of the string can be calculated using the following data:

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

Otherwise, for wire sizing, a voltage multiplication factor, as alternative option with maximal accounting temperature coefficient, could be used:

$$V_{OC\,MAX\,string} = V_{OC\,STC\,string} \cdot 1.15 \qquad (4.4)$$

where $V_{OC\,STC\,string}$ – string open circuit voltage at STC, calculate as:

$$V_{OC\,STC\,string} = N_{Module} \cdot V_{OC\,STC} \tag{4.5}$$

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

$$I_z \geq I_{SC\,MAX\,string} \tag{4.6}$$

As already introduced in the paragraph 1.2.1, in a series connection of modules the current does not add up; the total current in a string of PV modules connected in series is equal to the current generated by the single module. The maximum string short-circuit current $I_{SC\,MAX\,string}$ is equal to the maximum PV module short-circuit current $I_{SC\,MAX\,module}$ and, as already introduced in the paragraph 3.5, it can be calculated using the following data:

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

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

$$I_z \geq I_{SC\,MAX\,string} = I_{SC\,STC\,string} \cdot 1.25 \tag{4.7}$$

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

4.1.2 Array cables

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

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

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

$$I_z \geq I_{SC\ MAX\ array} = N_{string} \cdot I_{SC\ MAX\ string} = N_{string} \cdot I_{SC\ STC\ string} \cdot 1.25 \qquad (4.8)$$

To calculate the voltage drop in the next *section* ($V_{OC\ MAX\ array}$) after *string*, it is necessary to take the voltage of the section taking into account the voltage drop of the previous section:

$$V_{OC\ MAX\ array} = V_{OC\ MAX\ string} - \partial V_{\max} \qquad (4.9)$$

All the next stages of cross-section selection must take into account all pre

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

4.2 Protection against overcurrent on DC side

4.2.1 Cable protections

It is not necessary to protect PV string cables against overloads if they are chosen with a current carrying capacity $\left(I_{cu\ string}\right)$ equal to or greater than 1.25 times the I_{sc}:

$$I_{cu\ string} \geq 1.25 \cdot I_{SC} \qquad (4.10)$$

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

$$I_{cu\ sub-array} \geq 1.25 \cdot S_{SA} \cdot I_{SC} \tag{4.11}$$

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

It is not necessary to protect the PV array cables against overloads if they are chosen with a current carrying capacity $\left(I_{cu\ array}\right)$ equal to or greater than 1.25 times the sum of the I_{sc} of the array strings:

$$I_{cu\ array} \geq 1.25 \cdot S_{A} \cdot I_{SC} \tag{4.12}$$

where S_{A} – the number of parallel-connected PV strings in the PV array (Figure 4.1).

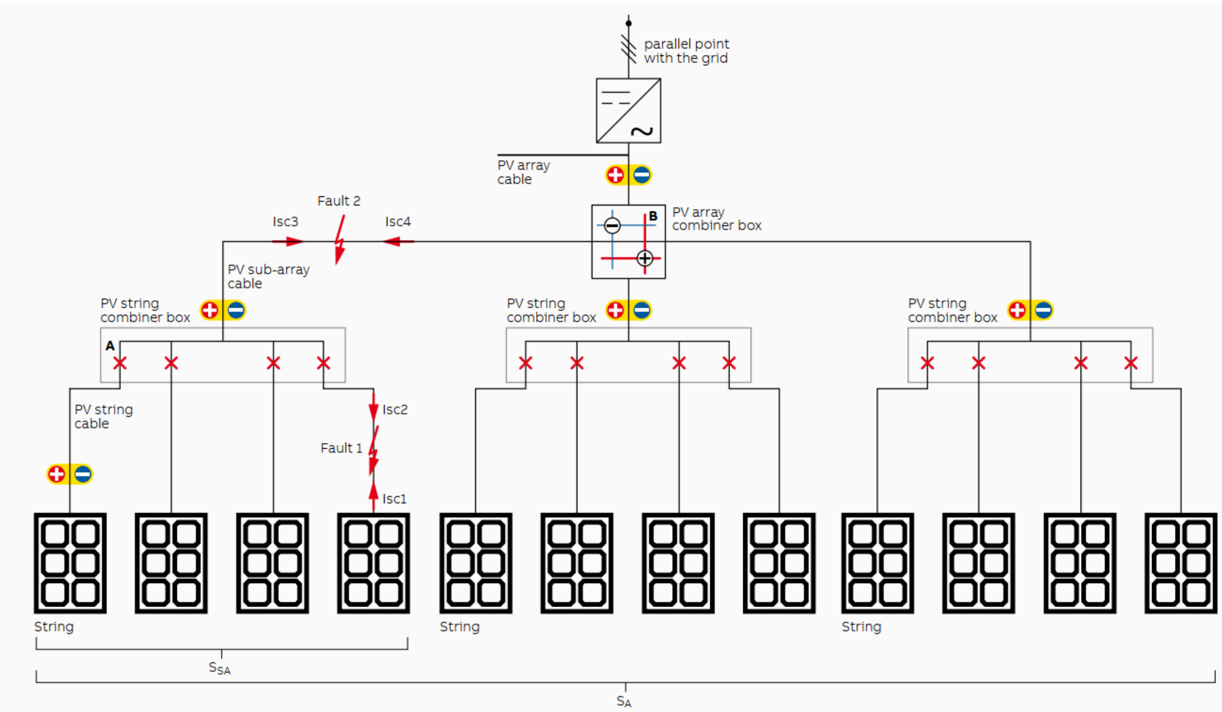


Figure 4.1 – Array, sub-array and strings cables faults

On Figure 4.1: ***A*** represents the protective device installed in the PV string combiner box; ***B*** represents the protective device installed in the PV array combiner box; $\boldsymbol{S_{SA}}$ is the number of parallel-connected PV strings in the PV sub-array; $\boldsymbol{S_{A}}$ is the total number of parallel-connected PV strings in the PV sub-array.

Regarding short-circuit, overcurrent within a PV array could occur on the DC cables of PV generator in case of:

- fault between the polarity of the PV system (short circuits in PV generator components);
- fault to earth in the earthed systems;
- double fault to earth in the earth-insulated systems.

PV modules are current limited sources and their short-circuit current (I_{sc}) value is just higher than the operative current (I_{MPP}). In case of short-circuit affect the string cables or connectors (Fault 1 in the Figure 4.1), the string cable is supplied:

- upstream by the string under consideration $\left(I_{SC1} = 1.25 \cdot I_{SC}\right)$;
- downstream by the other $\left(S_A - 1\right)$ strings connected $\left(I_{SC2} = 1.25 \cdot (S_A - 1) \cdot I_{SC}\right)$.

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

$$I_{SC2} = 1.25 \cdot (2 - 1) \cdot I_{SC} = I_{SC1} \quad (4.13)$$

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

$$I_{SC1} > I_{SC2} \quad (4.14)$$

Therefore, the cables and the string connectors must be protected against the short-circuit when their current carrying capacity is lower than Isc2.

$$1.25 \cdot I_{SC} \leq I_{z\,string} < I_{SC2} = 1.25 \cdot \left(S_A - 1\right) \cdot I_{SC} \quad (4.15)$$

In case of short-circuit affect the cables between a PV string combiner box and the PV array combiner box (Fault 2 in the Figure 4.1), the string cable is supplied:

- upstream by the PV sub-array string $\left(I_{SC3} = 1.25 \cdot S_{SA} \cdot I_{SC}\right)$;

- downstream by the other $\left(S_A - S_{SA}\right)$ strings connected $\left(I_{SC4} = 1.25 \cdot \left(S_A - S_{SA}\right) \cdot I_{SC}\right)$.

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

$$I_{SC4} = 1.25 \cdot \left(2S_A - S_A\right) \cdot I_{SC} = 1.25 \cdot S_A \cdot I_{SC} = I_{SC3} \tag{4.16}$$

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

$$I_{SC4} > I_{SC3} \tag{4.17}$$

Therefore, the cables must be protected against the short-circuit when their current carrying capacity is lower than I_{SC4}.

$$1.25 \cdot S_{SA} \cdot I_{SC} \le I_{z\ sub-array} < I_{SC4} = 1.25 \cdot \left(S_A - S_{SA}\right) \cdot I_{SC} \tag{4.18}$$

4.2.2 Protection of strings against reverse current

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

In case of S_A strings connected in parallel, the highest reverse current $\left(I_{rev\max}\right)$ is equal to:

$$I_{rev\max} = \left(S_A - 1\right) \cdot I_{SC} \tag{4.19}$$

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

4.2.3 Contribution of the inverter

The contribution to short-circuit on the DC side of the inverter may come from the grid and from the discharge of the capacitors inside the inverter. The grid short-circuit current is due to the free-wheeling diodes of the inverter which in this case acts as a bridge rectifier. Such current is limited by the impedances of the transformer and of the inductors belonging to the output circuit. In case of inverter with galvanic insulation at 50 Hz, this current exists.

In case of inverter without galvanic insulation (transformer-less inverters), usually it has a DC/DC converter in input; so that the operation of the PV generator on a wide voltage range is guaranteed; if the DC/DC converter is boost converter, due to its constructive typology, includes at least one blocking diode which prevents the grid current from contributing to the short-circuit; if the DC/DC converter is buck converter, due to its constructive typology, it is not able to prevent the grid current from contributing to the short-circuit.

The discharge current of the capacitors is limited by the cables between inverter and fault and exhausts itself with exponential trend: the lowest the impedance of the cable stretch, the highest the initial current, but the lowest the time constant of the discharge. The energy which flows is limited to that one initially stored in the capacitors.

In case of blocking diode installed in series with one of the two poles, the contribution to short-circuit is null.

In case of a very high discharge current of the capacitors, associated to long time constants, an increase in the breaking capacity of the circuit-breakers could be required.

4.3 Choosing of protective devices

4.3.1 Choosing of String protective devices

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

- be obviously suitable for DC usage;
- have a rated service voltage equal or higher than the PV string/array maximum voltage (paragraph 1.4.2);
- have an IP rating suitable for the installation location and environment;
- have a temperature rating appropriate to the installation location and application.

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

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

$$1.5 \cdot I_{SC} \le I_n < 2.4 \cdot I_{SC} \tag{4.20}$$

$$I_n \le I_{rev\,module} \tag{4.21}$$

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

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

$$1.5 \cdot S_g \cdot I_{SC} < I_{n\,g} < \left\{ I_{rev\,module} - \left[\left(S_g - 1 \right) \cdot I_{SC} \right] \right\} \tag{4.22}$$

where: S_g – the number of strings in a group under the protection of the one overcurrent device;

$I_{n\,g}$ – the nominal overcurrent protection rating of the group overcurrent protection device.

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

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

- *gPV* fuses, in accordance with the IEC 60269-6 standard, connected in series to the individual string; despite the easy usage of fuses, attention must be paid to the sizing and choice of such devices, which shall not only have rated current given by the previous formulas, but also tripping characteristic type *gPV* (IEC 60269-6), shall be inserted into suitable fuse holders and be able to dissipate the power generated under the worst operating conditions. In accordance with IEC 60364-7-712 both polarities shall be protected.

- string diode connected in series with the individual string: it can prevent any reverse current in the protected string. In case of diode failure, it may cause the loss of the safety function and/or involve the string failure. Moreover, the string current flows always through the diode connected in series and the string diode generate continuous losses. Blocking diodes are not common in a grid connect system because their function is better served by the installation of a string fuse. By the way, for multi-string arrays with thin-film PV modules, provide adequate overcurrent / reverse current protection with string fuses or MCB (miniature circuit-breaker) couldn't be possible (it may not be possible to specify a fuse / MCB which is greater than 1.25 times the $I_{SC} \cdot 1.25$ and at the same time smaller than the reverse current rating of the module). In this situation blocking diodes should be used in addition to string fuses. As shown at Figure 4.2.

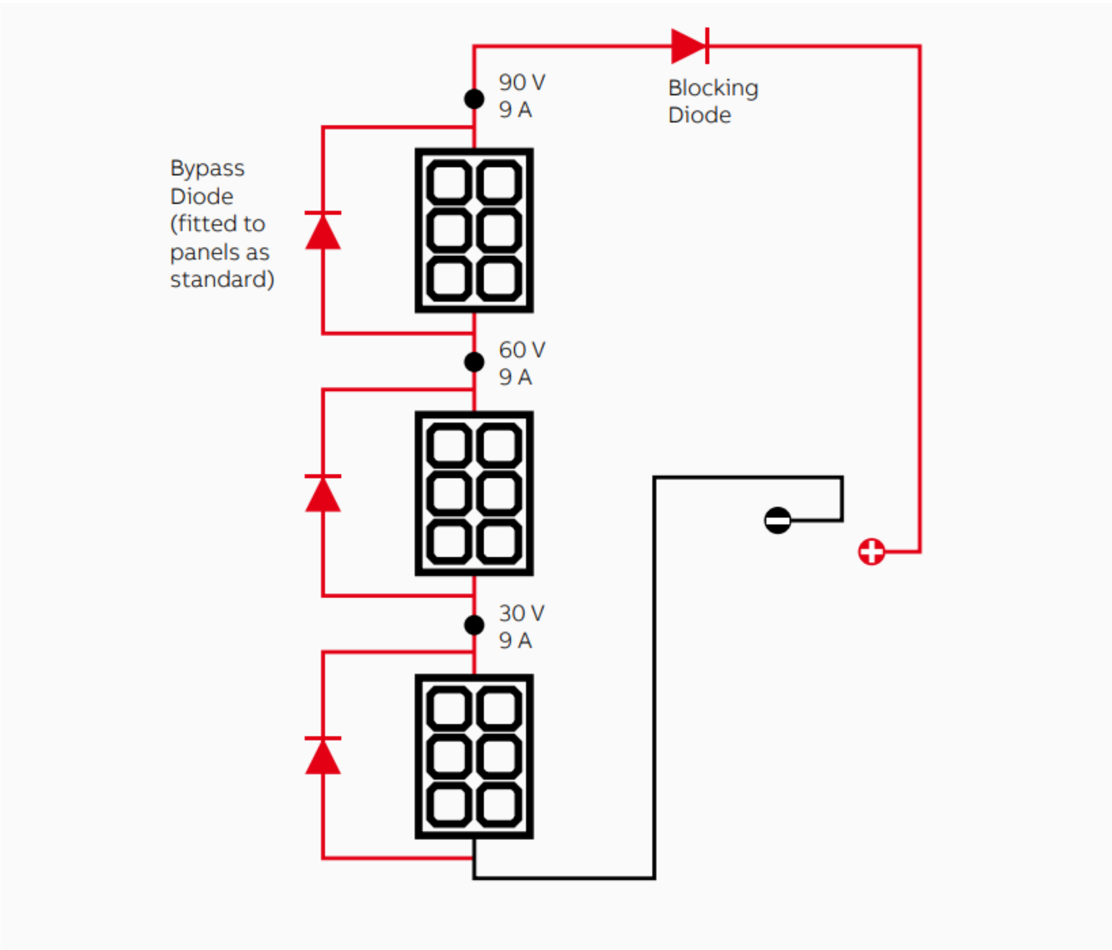


Figure 4.2 – Blocking diode installation

The blocking diode must have:

- A reverse voltage rating > 2 times the maximum system voltage;

- A current rating > 1.4 times the I_{sc} (where I_{sc} is the relevant short-circuit current for the string / sub array / array);
- An adequate cooling.
- MCB – miniature circuit-breaker (thermomagnetic circuit-breakers) with overcurrent protection elements (in accordance with IEC 60898-2): it shall meet the string fuse criteria and it shall be rated for use in an inductive circuit and allow DC currents flowing in either direction through the device. When miniature circuit-breaker with overcurrent protection elements is used, it may also provide the disconnecting means to isolate both polarity of the PV array from the power conversion equipment and vice versa and to allow for maintenance and inspection tasks to be carried out safely. The miniature circuit-breaker with overcurrent protection elements are designed to be used at a defined ambient temperature: in case of overtemperature in the combiner box, the miniature circuit-breaker with overcurrent protection elements is derated; the maximum operation temperature should be verified in advance during the design of the miniature circuit-breaker to avoid unexpected triggering.

In order to protect sub-array cables against overcurrent and/or reverse current usually *gPV* fuses, in accordance with the IEC 60269-6 standard, connected in series to the sub-array cables could be used. Also MCB (Miniature Circuit-Breakers) or MCCB (Molded Case Circuit-Breaker) connected in series to the sub-array cables could be used.

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

$$1.25 \cdot S_{SA} \cdot I_{SC} < I_n < 2.4 \cdot S_{SA} \cdot I_{SC} \tag{4.23}$$

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

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

$$I^2 \cdot t \le K^2 \cdot S^2 \tag{4.24}$$

where $I^2 \cdot t$ – the Joule integral for the short-circuit duration (in A^2s);

K – a characteristic constant of the cable, depending on the type of conductor and isolating material;

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

In case of each PV string is protected with an overcurrent protection device, the rated ultimate short-circuit breaking capacity (I_{cu}), of the devices in the PV string combiner box, must be not lower than the short-circuit current of the other $(S_A - 1)$ strings:

$$I_{cu} \geq 1.25 \cdot (S_A - 1) \cdot I_{SC} \quad (4.25)$$

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

$$I_{cu} \geq 1.25 \cdot (S_A - S_g) \cdot I_{SC} \quad (4.26)$$

The devices in the PV array combiner box must protect against short-circuit the sub-array cables when these cables have a current carrying capacity lower than (c.f. Figure 4.1):

$$I_{SC4} = 1.25 \cdot (S_A - S_{SA}) \cdot I_{SC} \quad (4.27)$$

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

$$1.25 \cdot S_{SA} \cdot I_{SC} < I_n < 2.4 \cdot S_{SA} \cdot I_{SC} \quad (4.28)$$

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

$$I_{cu} \geq 1.25 \cdot (S_A - S_{SA}) \cdot I_{SC} \quad (4.29)$$

Table 4.2 – Technical data of Fuses 1000 *V*

Model	Rated Current (*A*)	Rated Voltage (V_{DC})	I^2t (A^2s) Pre-earcing	I^2t (A^2s) Total Power
1A10	1	1000	0.9	1.9
2A10	2	1000	1.3	3.7
3A10	3	1000	4.4	12.1
4A10	4	1000	10.5	28.6
5A10	5	1000	20.0	55.0
6A10	6	1000	33.0	99.0
8A10	8	1000	1.9	41.0
10A10	10	1000	2.4	52.0
12A10	12	1000	4.2	93.0
15A10	15	1000	5.6	143.0
16A10	16	1000	7.4	165.0
20A10	20	1000	16.7	372.0
25A10	25	1000	33.5	747.0
30A10	30	1000	38.5	1129.0
32A10	32	1000	43.1	1038.0

Table 4.3 – Technical data of Fuses 1500 *V*

Model	Rated Current (*A*)	Rated Voltage (V_{DC})	I^2t (A^2s) Pre-earcing	I^2t (A^2s) Total Power
2A15	2	1500	3	10
3A15	3	1500	8	22
4A15	4	1500	17	33
5A15	5	1500	35	63
6A15	6	1500	36	83
8A15	8	1500	39	110
10A15	10	1500	50	153
12A15	12	1500	17	226
15A15	15	1500	45	320
16A15	16	1500	50	380
20A15	20	1500	118	810
25A15	25	1500	202	1560
30A15	30	1500	280	1842
32A15	32	1500	330	2890

4.3.2 Positioning of overcurrent protection devices

Overcurrent protection devices shall be placed (IEC 62548):

- for string overcurrent protection devices, they shall be where the string cables join the sub-array or array cables in the string combiner box;

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

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

4.3.3 Choosing of switching and disconnecting devices

The installation of a disconnecting device on each string is recommended to allow verification or maintenance interventions on the string without putting out of service other parts of the PV plant. The disconnection of the inverter must be possible both on the DC side as well as on the AC side so that maintenance is allowed by excluding both the supply sources (grid and PV generator) (IEC 60364-7). On the DC side of the inverter a disconnecting device shall be installed which can be switched under load, such as a switch-disconnector. On the AC side a general disconnecting device31 shall be provided. The protective device installed at the connection point with the grid can be used; if this device is not close to the inverter, it is advisable to install a disconnecting device immediately on the load side of the inverter.

The DC switch is an equipment that manually separates the entire PV array from inverter. The array separation may be required for safety reasons or maintenance. The DC switch is located close to the inverter or in the combiner box. When choosing a DC switch, the following parameters are taken into consideration:

- Rated insulation voltage U_i;
- Rated operating voltage U_e;
- Rated operating current I_e.

The rated insulation voltage U_i should never be less than the open-circuit voltage V_{OC}. The rated operating voltage U_e of the switch should always be greater than the voltage level at which the current failure occurs. The value of U_e depends on the dielectric strength and the distance between the internal conductor and the creep. The rated operating current I_e of the switch should be greater than the total short-circuit currents of the PV array. If any of the parameters U_i, U_e, or I_e is not selected properly, it can cause switch malfunction that in turn poses safety hazards to the end user.

Rated operating current calculate as I_e, *A*:

$$I_e > \frac{I_{SC\,MAX\,Array}}{k_T} \tag{4.30}$$

where $I_{SC\,MAX\,Array}$ – the total short-circuit current of the array;

k_T – the switch derating factor, determined by Figure 4.3.

The IEC 60947-3 standard provides the technical specifications of various types of switches. For example, the DC-21B switch is suitable for average overloads where the shutoff operation is less likely to occur. This type of switch is usually employed for PV power plants. For the switch selection, there are noticeable differences between the recommendations provided by the UL 98 and UL 508 standards and the IEC 60947 and National Electrical Code (NEC) standards.

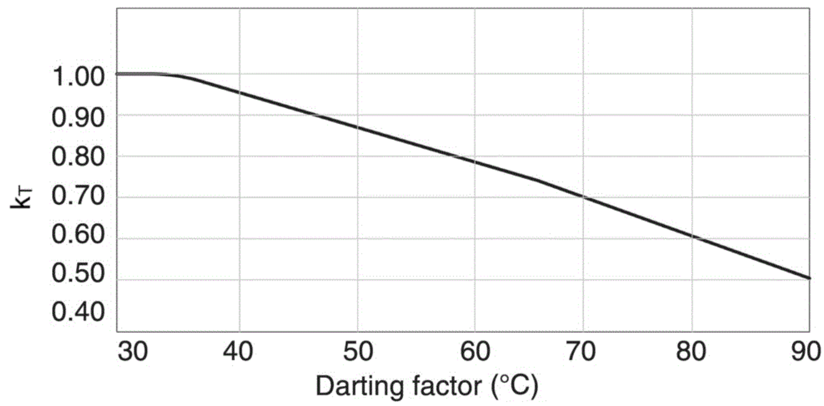


Figure 4.3 – Determining curve k_T

Table 4.4 – Technical data of switch-disconnectors

Name	SD 50	SD 75	SD 100	SD 160	SD 200	SD 250	SD 315	SD 400	SD 500
Nominal current I_n, *A*	50	75	100	160	200	250	315	400	500
Number of poles	2, 3, 4								
Maximum voltage U_e, *V*	1500								
Maximum operating temperature in box without $I_{th} \cdot$ *derating*, °C	40								

Self-testing questions for Chapter 4

1) What standards should be followed for sizing cables in DC equipment selection?

2) How is the cross-sectional area of a conductor selected according to the document?

3) What is the formula for calculating the minimal allowance cross-section of a cable?

4) What factors should be taken into account when determining the cross-sectional area of a cable?

5) What is the significance of the specific resistance of the cable material in cable selection?

6) What is the maximum percentage of voltage drop allowance recommended for cables?

7) How is the maximum open circuit voltage with voltage multiplication factor calculated?

8) What is the purpose of overcurrent protection devices in DC equipment?

9) What criteria should a miniature circuit-breaker (MCB) meet according to IEC 60898-2?

10) How is short-circuit current limited in an inverter with galvanic insulation at 50 Hz?

5 CONFIGURATION OF SOLAR PHOTOVOLTAIC POWER PLANT ON AC SIDE

5.1 Network schemes

In case of utility scale PV plant directly connected to the DSO MV grid, the designer shall size also the MV electric network of the PV plant correctly; it is necessary to do the following network calculations either entirely or partly:

- sizing calculations (transformers, etc.);
- calculation of the short-circuit currents;
- definition of the status of the neutral;
- study of protection coordination.

Before all these activities, the single-line diagram of the PV plant MV electric network shall be defined on the basis of:

- inverter and transformer position;
- electric network structure.

The advantages and disadvantages of the different MV network solutions shall be considered and, after that, according to the PV plant MV electric network designed, also the protections shall be selected.

An electrical transformer substation consists of a whole set of devices (conductors, measuring and control apparatus and electric machines) dedicated to transforming the voltage supplied by the medium voltage distribution grid (e.g. 15kV or 20kV), into voltage values suitable for supplying low voltage lines with power (400V - 690V)

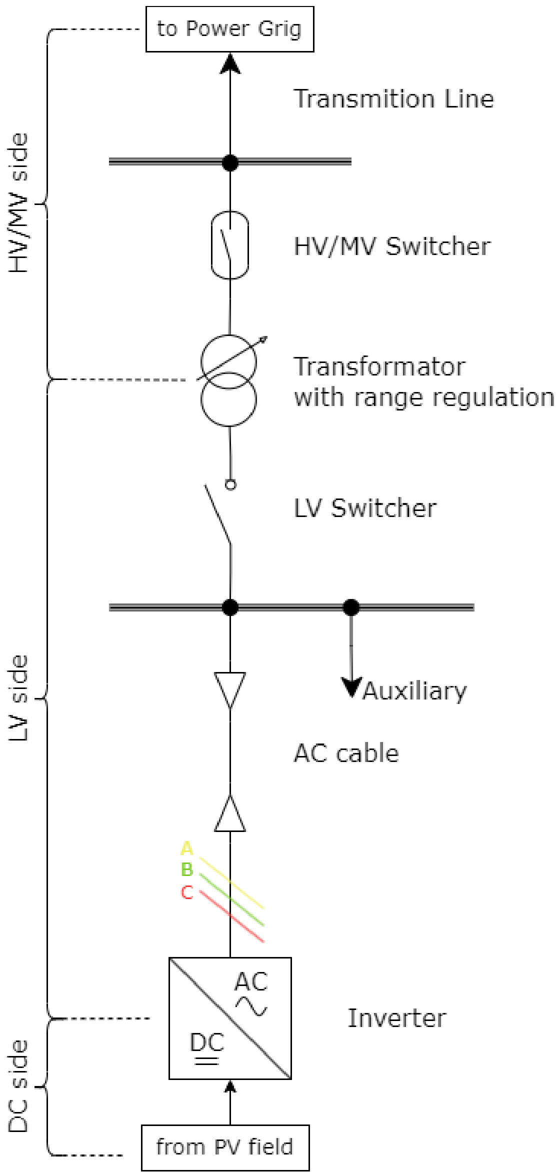


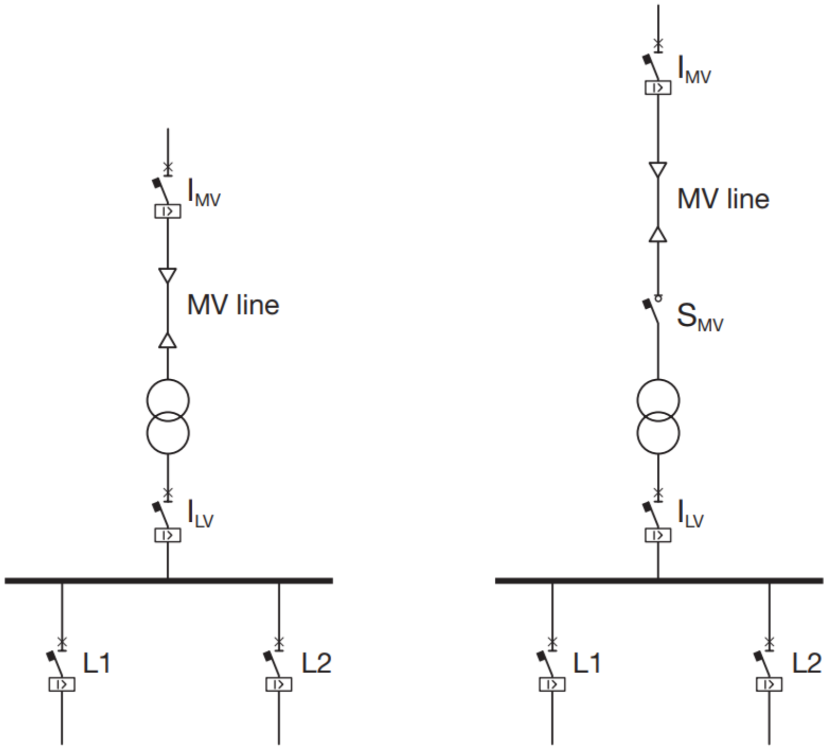
Figure 5.1 – Base structure

5.1.1 Substation with a single transformer

When the plant foresees installation of an “I_{MV}” overcurrent protection device where the line which supplies the substation originates, as shown in Figure 5.2 (a), this device must ensure protection of both the MV line as well as the transformer.

In the case where the protection device also carries out switching and isolation functions, an interlock must be provided which allows access to the transformer only when the power supply line of the substation has been isolated.

Another management method is shown in Figure 5.2 (b), which foresees installation of the “S_{MV}” switching and isolation device positioned immediately to the supply side of the transformer and separate from the protection device which remains installed at the beginning of the line.



(a) (b)

Figure 5.2 – Substation with a single transformer, N_{tr}=1

5.1.2 Substation with two transformers with one as a spare for the other

When the plant foresees installation of a transformer considered as a spare, the circuit-breakers on the LV side must be connected with an "I" interlock whose function is to prevent the transformers from operating in parallel as shown in Figure 5.3.

Apart from the switching and isolation device on the incoming MV line (I_{GMV}), it is advisable to provide a switching, isolation and protection device on the individual MV risers of the two transformers (I_{MV1} and I_{MV2}) as well. In this way, with opening of the device on the supply and load side of a transformer, it is possible to guarantee isolation and access the machine without putting the whole substation out of service.

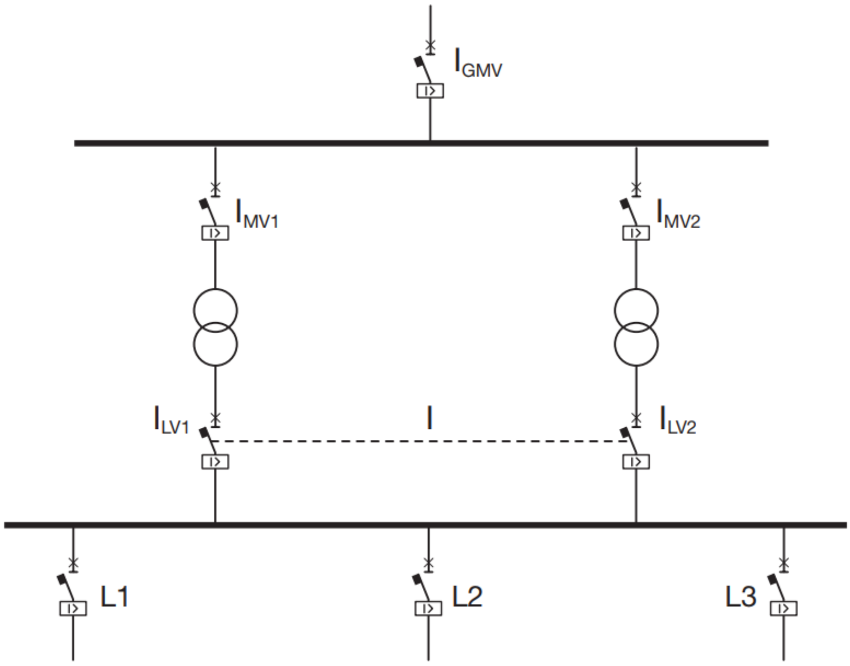


Figure 5.3 – Substation with two transformers with one as a spare for the other, N_{tr}=2

5.1.3 Substation with two transformers which operate in parallel on the same busbar

When the plant foresees installation of two transformers operating in parallel at the same overall power required of the plant, it is possible to use two transformers with lower rated power as shown in Figure 5.4. Compared with the management method described in the two previous cases, higher short-circuit currents could be generated for faults in the low voltage system due to reduction of the possible $v_{k\%}$ for lower power machines.

Operation in parallel of the transformers could cause greater problems in management of the network. Again, in this case, however, outage of a machine might require a certain flexibility in load management, ensuring the power supply of those considered to be priority loads. When coordinating the protections, the fact that the overcurrent on the LV side is divided between the two transformers must be taken into consideration.

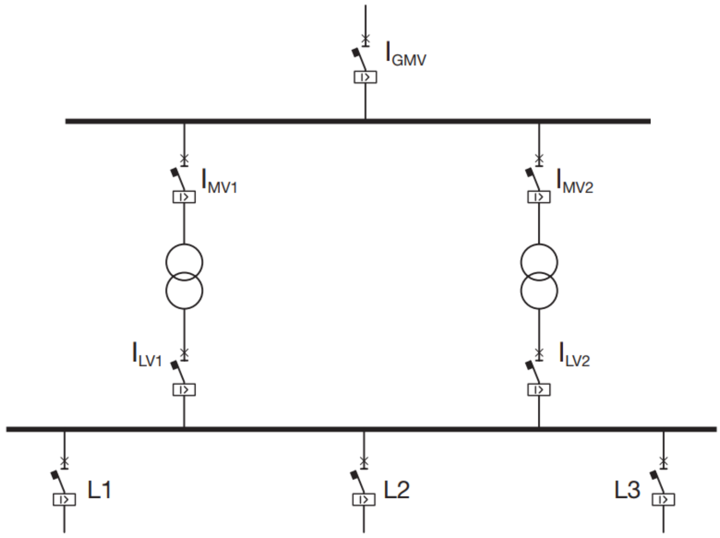


Figure 5.4 – Substation with two transformers which operate in parallel on the same busbar, N_{tr}=1

5.1.4 Substation with two transformers which operate simultaneously on two separate half-busbars

Starting from the previous management method, by providing a “C_{LV}” bus-tie and an “*I*” interlock which prevents the bus-tie from being closed when both the incoming circuit-breakers from the transformer are closed, a substation managed as shown in Figure 5.5 is made, which foresees two transformers which individually supply the low voltage busbars, which are separate.

With the same power of the transformers installed, this management method allows a lower value of the short-circuit current on the busbar. In other words, each transformer establishes the short-circuit level for the busbar of its competence without having to consider the contribution of other machines. Again, in this case, when a transformer is out of service, with any closure of the bus-tie you pass to a system with a single busbar supplied by the sound transformer alone, and a load management logic must be provided with disconnection of non-priority loads.

Plant management according to Figure 5.5 is possible, for example by using the Emax series of air circuit-breakers with a wire interlock (mechanical interlock) between three circuit-breakers.

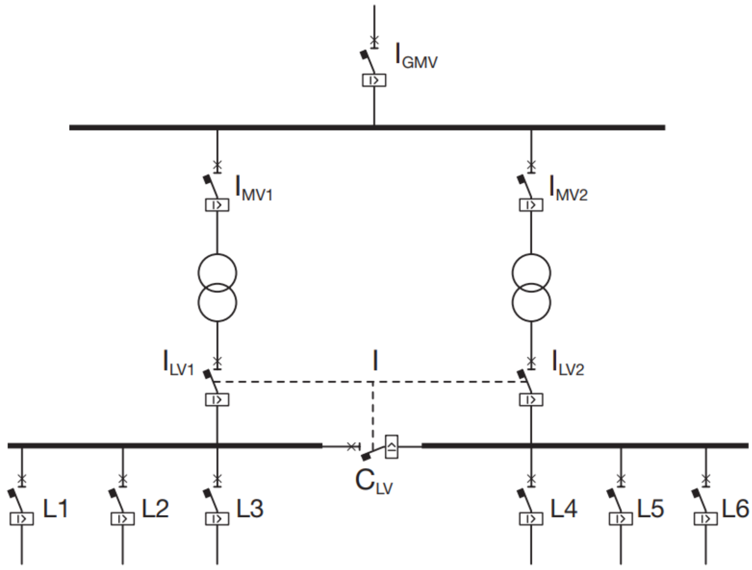


Figure 5.5 – Substation with two transformers which operate simultaneously on two separate half-busbars, N_{tr}=1

5.2 Power Transformers

The transformer is the most important part of the transformer substation. Its selection affects the configuration of the substation and is made on the basis of various factors.

Not being a specific subject of this paper and wanting to give some general indications, it can be stated that for the request for low powers (indicatively up to 630 *kVA* – 800 *kVA*), a single transformer can be installed, whereas for higher powers (indicatively up to 1000 *kVA* – 1600 *kVA*), the power is divided over several units in parallel.

Another characteristic to take into consideration when selecting the machine is the type of cooling system, which can be either in air or in oil. With reference to air conditioning the structure of the substation, in the case of oil cooled transformers, measures must be taken, for example those to prevent the oil spreading outside by providing an oil collection pit. Furthermore, the substation must have a minimum flame resistance of 60 minutes (REI 60) and ventilation only towards the exterior. According to the type of cooling, the transformers are identified as follows:

- ***AN*** cooling with natural air circulation;
- ***AF*** cooling with forced air circulation;
- ***ONAN*** cooling with natural oil and air circulation;
- ***ONAF*** cooling with forced oil and natural air circulation;
- ***OFAF*** cooling with forced oil and air circulation.

The most frequent choice is for ***AN*** and ***ONAN*** types, as it is not advisable to use machines which use fans or oil circulators because it is rarely possible to man the substations.

Other important characteristics to be considered are those referring to the electrical parameters and, in addition to the usual quantities such as rated power, no-load secondary rated voltage, transformation ratio, rated short-circuit voltage in percent $v_{k\%}$, they acquire great importance above all when the transformers are functioning in parallel:

- the connection typology of the windings (delta/star grounded is the most used one for the substation transformers)
- connection system, conventionally expressed by a number which, multiplied by 30, gives the delay angle of the phase voltage on the LV side compared with the MV side.

The presence of two or more MV/LV transformers and a possible bus-tie closed on the LV busbars allows the electricity network to be managed with the transformers in parallel.

In the presence of faults, this management method causes an increase in the short-circuit current value on the LV side, with a possible consequent increase in the size of the circuit-breakers outgoing from the busbar and heavier anchoring conditions for the busbars in comparison with operation with a single transformer. This is due to a smaller value of the $v_{k\%}$ which characterizes the transformers with less power. On the other hand, when suitably managed, the parallel method has the advantage of allowing power supply, at least to the users considered as primary users, through the possible bus-tie, even in the case of outage of one of the transformers.

Selection of transformers consists in determining their number, type and rated power. It is recommended to use three-phase transformers. In those cases when it is impossible to select three-phase transformers, it is allowed to use a group of two three-phase transformers. When choosing three-phase transformers for solar photovoltaic power plants, they must have voltage regulation devices under load.

Rated power of transformer S_{tr} is define from nominal range, according to condition:

$$S_{tr} \geq S_{nom} \tag{5.1}$$

where S_{nom} – nominal, calculated, power of transformer:

$$S_{nom} = \frac{S_{\Sigma PV}}{N_{tr} \cdot k_{ol}} \tag{5.2}$$

where $S_{\Sigma PV}$ – maximum output power of invertor;

N_{tr} – the number of transformers;

k_{ol} – the transformer overloading coefficient, which considering possible overloading of transformer to 40%, $k_{ol} = 1.4$.

Table 5.1 – Parameters of three-phase, dry-insulated Solar Energy Application Transformers

Type	Rated Power, *kVA*	HV, *kV*	LV, *V*	Impedance, %	No-load loss, *W*
ST-25	25	12.5/25/34.5	277/480	5.75	220
ST-40	40				310
ST-63	63				420
ST-100	100				450
ST-160	160				530
ST-200	200				610
ST-250	250			5.9	700
ST-300	300				810
ST-400	400				990
ST-500	500				1100
ST-630	630				1310
ST-800	800				1510
ST-1000	1000				1710
ST-1250	1250			6	1990
ST-1500	1500				2350
ST-1600	1600				2760
ST-2000	2000				3400
ST-2500	2500				4000
ST-3150	3150				4600
ST-4000	4000				5200

5.3 HV/MV switchgear

High-voltage substations are points in the power system where power can be pooled from generating sources, distributed and transformed, and delivered to the load points. Substations are interconnected with each other, so that the power system becomes a meshed network. This increases the reliability of the power supply system by providing alternate paths for flow of power to take care of any contingency, so that power delivery to the loads is maintained and the generators do not face any outage.

The high-voltage substation is a critical component in the power system, and the reliability of the power system depends upon the substation. Therefore, the circuit configuration of the high-voltage substation has to be selected carefully and designed. Busbars are that part of the substation where all the power is concentrated from the incoming feeders and distributed to the outgoing feeders.

That means that the reliability of any high-voltage substation depends on the reliability of the busbars present in the power system. An outage of any busbar can have dramatic effects on the power system. An outage of a busbar leads to the outage of the transmission lines connected to it.

As a result, the power flow shifts to the surviving healthy lines that are now carrying more power than they are capable of. This leads to tripping of these lines, and the cascading effect goes on until there is a blackout or similar situation. The importance of busbar reliability should be kept in mind when taking a look at the different busbar systems that are prevalent.

The three-phase high-voltage systems are found in the combined operation, in cities and in industrial centers. The voltage level is determined by the transmission and short-circuit power. The switchgear is designed as interior room or outdoor switchyard. For the configuration and calculation of switchgear of the scope of the system and the number of the busbars and their equipment is very important.

*Substation layouts depend on the number of lines and transformers connected at a given voltage.*To choose Switchgear type we need to know Voltage level, and Number of connections.

Number of switchgear connections include: Number of transformers and Number of Transmission connection (Transmission Line or Power Cables).

Number of Transmission connections calculate as:

$$N_{TL} = \frac{P_{PVPP}}{P_{TC}} \tag{5.3}$$

where P_{PVPP} – active Power of whole PV Power Plant, *MW*;

P_{TC} – transition capacity of Transmission Line or Power Cables (Table 5.2), *MW*.

In case your calculated number are not whole you must round it up.

Table 5.2 – Characteristics of the transmission capacity of Transmission Line

Nominal voltage, *kV*	Limited distance under efficiency 90*% per km*	Transmission capacity, *MW*
6 (10)	5	2.1
20	8	7.5
35	20	15
110	80	50

5.3.1 Switchgear 6-10 kV (7.2-24 kV)

Switchgear of 6-10 (7.2–24) *kV* and higher usually designed as indoor type.

At Figure 5.6, a) shown base structure of switchgear, it can be modified according to calculated number of switchgear connections and needed systems of measurement (as Measurement Current and Voltage transformers). At Figure 5.6, b) shown view of switchgear cells.

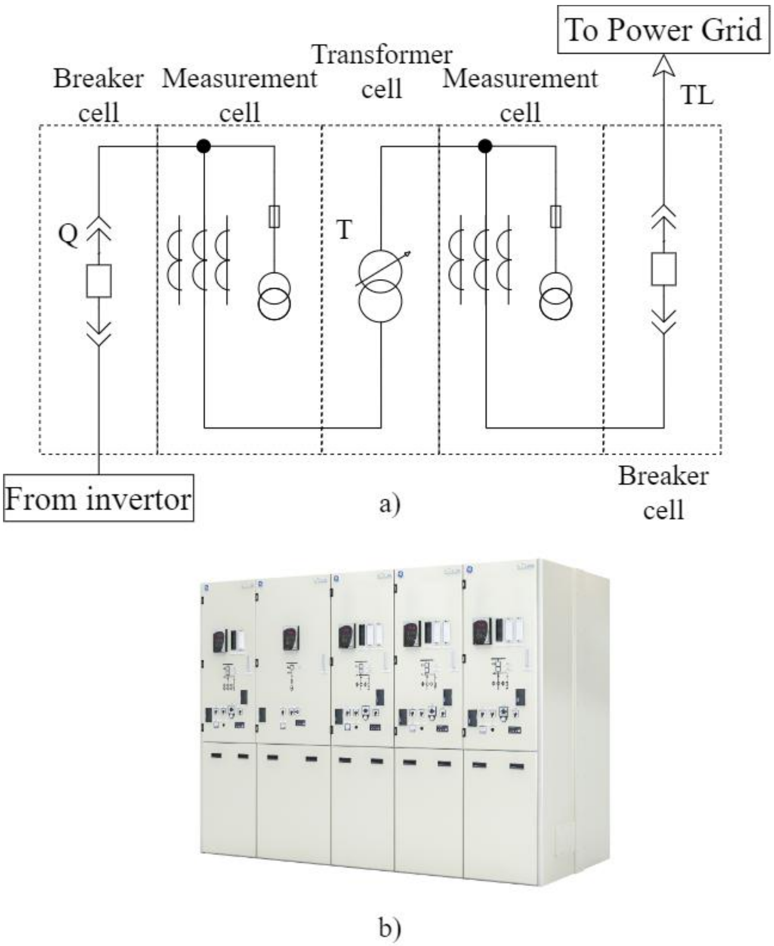


Figure 5.6 – Design of MV Switchgear 6–24 *kV*, indoor type

5.3.2 Switchgear 35 kV (34.5 kV)

Switchgear of 35 *kV* and higher usually designed as outdoor type.

"Transformer-line" scheme (Figure 5.7). The scheme is used in the case of dead-end substations and is simple, economical and sufficiently reliable. However, if a line or transformer is damaged or repaired, the operation of the unit is disrupted, which leads to a complete loss of power in the case of using a single-transformer substation (Figure 5.7 *a*).

In the given substation diagrams (Figure 5.7, *a* and *b*), the protection of the power transformer acts to turn off the *Q* switch on the low-voltage side and turn on the short circuit *S*, with the help of which it is artificially created at a voltage of 110 *kV* single-phase, and at a voltage of 35 *kV* two-phase short circuit. In this case, the linear oil switch *Q* is disconnected from its own protection.

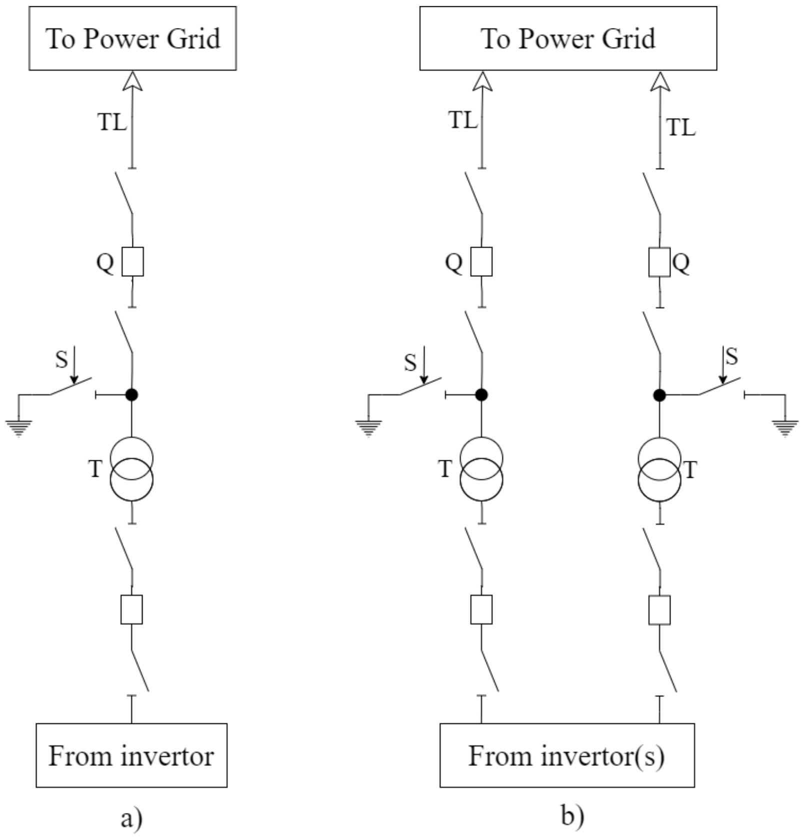


Figure 5.7 – Design of MV Switch-gear 35 *kV*: "Transformer – Transmission Line"

"Bridge" scheme (Figure 5.8, a). The circuit has a small number of switches on the high voltage side, so it allows you to disconnect any connection (line and transformer). The "Bridge" scheme is used for relatively high-power transformers, as well as long lines; scheme Figure 5.8, a) - if it is necessary to transit power along the lines.

Scheme "With one Busbar System" (Figure 5.8, b). The scheme is quite simple and reliable; Disconnectors are used only during repair work to disconnect circuits previously disconnected by switches. The disadvantage of the scheme is the need to disconnect all connections of the section when repairing busbars and busbar disconnectors. Must have ATS for sectionizing to increase reliability.

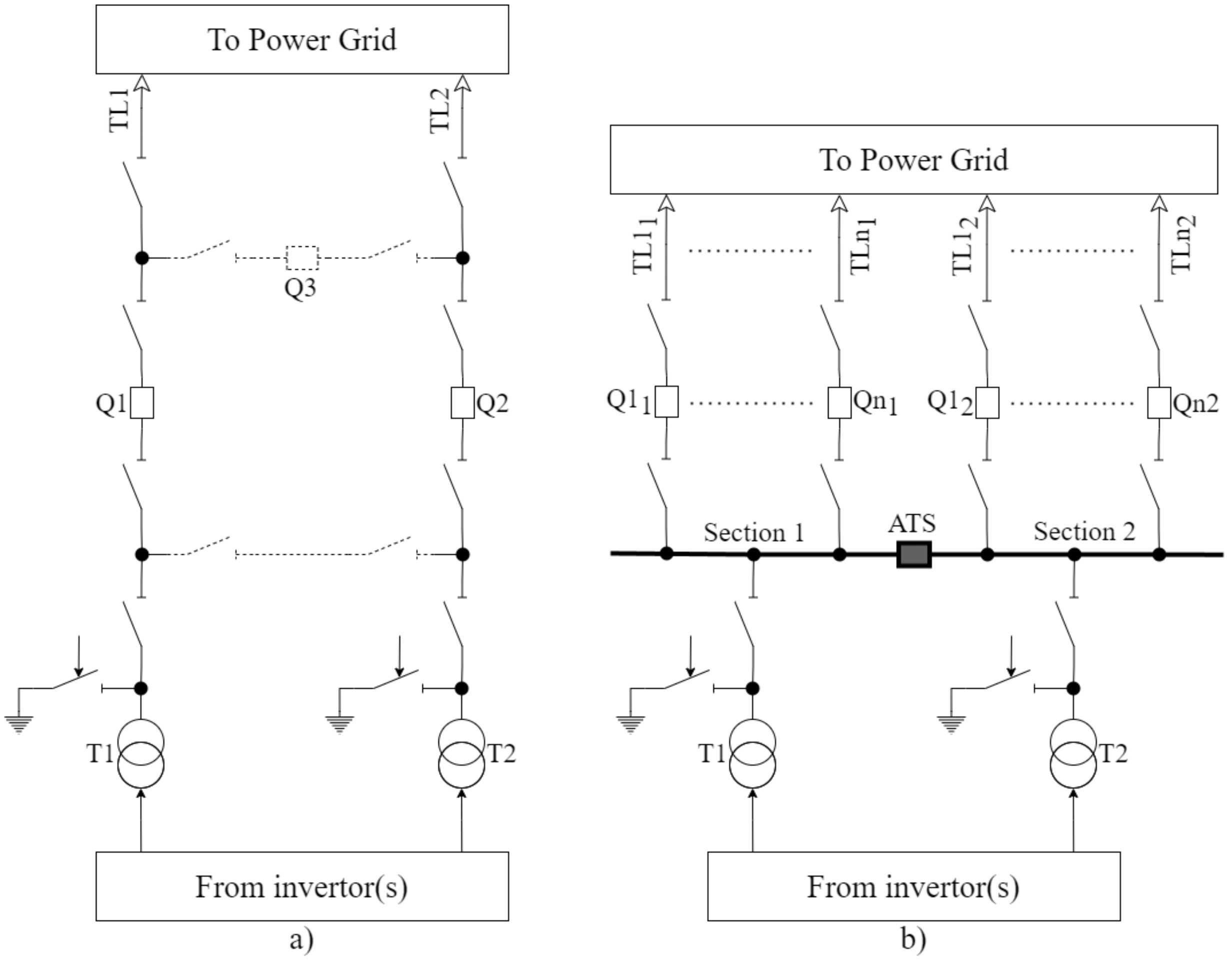


Figure 5.8 – Design of MV Switch-gear 35 *kV*: "Bridge" (a), and "Single Busbar with ATS" (b)

5.3.3 Switchgear 110 *kV* (137 *kV*)

For 110-220 *kV* switchgear with a large number of connections, a scheme with two working and bypass bus systems with one switch per circuit is used (Figure 5.9). As a rule, both bus systems are in operation with a corresponding fixed distribution of all connections: lines *TL1÷TLn* and from transformer *T* are connected to the bus system, bus coupling switch *QK* enabled. This distribution of connections increases the reliability of the circuit, since in the event of a short circuit on the buses, the bus coupling switch *QK* and only half of the connections are switched off. If the damage to the busbars is permanent, the disconnected connections are transferred to a working busbar system. The interruption of power supply to half of the connections is determined by the duration of the switching. The considered scheme is recommended for 110-220 *kV* switchgear on the HV and MV side of substations with a number of connections of 7÷15.

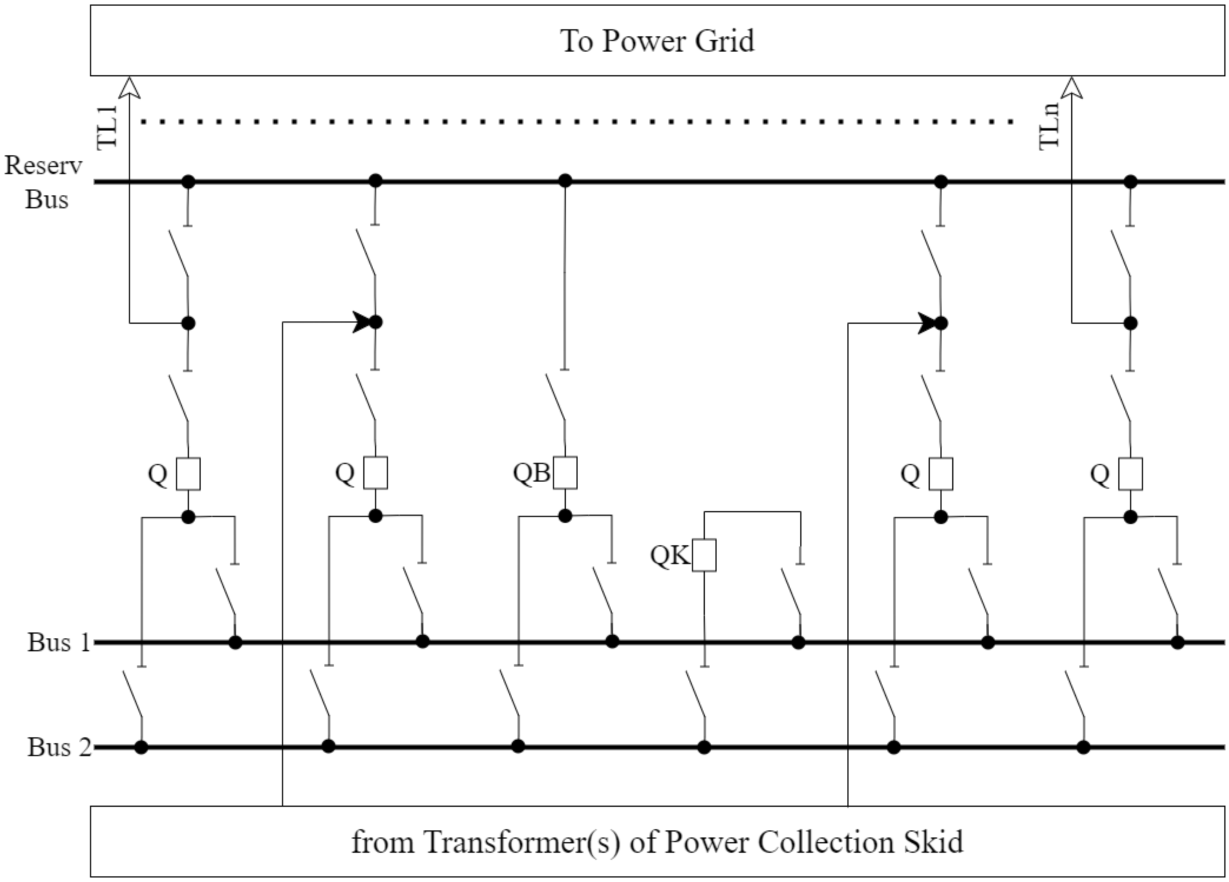


Figure 5.9 – Design of HV Switch-gear 110 *kV*

If number of connections less than 7, can be used scheme Figure 5.8.

5.4 AC Short-circuit

The connection of the PV plant to the grid must be designed in a way to safely withstand the mechanical and thermal effects of short-circuit currents. The characteristic values for dimensioning the connection system are typically provided by the grid operator at the grid connection point (for example, rated voltages and rated short-time current).

The purpose of short circuit studies is to investigate thermal effect of fault currents on power network components, coordination of protection equipment and relays, and determination of the cutoff power required for power switches. For the short circuit studies, the following cases should be investigated:

- various operating scenarios;

- presence and absence of the PV power plant;
- occurrence of various fault types;
- faults at different locations in the downstream and upstream of the PV power plant;
- faults inside the PV power plant and in its adjacent feeders.

The areas adjacent to the point of common coupling (PCC) are a priority for the short circuit studies since the connection of a PV power plant to the grid has the greatest impact on the PCC and its adjacent areas. For this reason, short circuit studies at the PCC and its adjacent areas are essential. In addition, the impacts of connecting a PV power plant to the grid on the required cutoff power of the switches at the PCC and the adjacent areas should be investigated. Short circuit studies should be performed for existing inverters in the PCC area to determine the effect of connecting the PV power plant to the grid. The capabilities of these inverters can be used to control short circuit currents. Inverters usually have the ability to participate in fault current in order to maintain their terminal voltage. Inverters can inject up to five times their rated current for a short period of a few tens of milliseconds.

The short-circuit is accidental or intentional contact, with relatively low resistance or impedance, between two or more points at different voltages in a circuit. The short-circuit current is an overcurrent resulting from a short-circuit due to a fault or to incorrect connection of an electric circuit.

From the theoretical point of view, calculation of the short-circuit currents should be processed using the data obtained from studying the voltage profiles. By the way, the Standards envisage that the calculation be made at the rated plant values and appropriate correction coefficients are introduced for compensation.

The short-circuit currents calculation is necessary to:

- establish adequate sizing of the operating and interruption parts;
- define the thermal and mechanical stresses of the plant elements;
- calculate and select the protection system settings;
- carry out suitable protection for people and the plants.

The short-circuit currents under the various different operating conditions shall be define in the study of an electric system:

- the maximum short-circuit currents are important for system sizing;
- the minimum short-circuit currents are important in order to protection coordination (the protection trip current must always be lower than the minimum short-circuit current at the point of connection).

Four different types of grid faults of MV power transmission line (Figure 5.10):

- single-phase grounded fault;
- two-phase short-circuit fault;
- two-phase grounded fault;
- three-phase short-circuit fault.

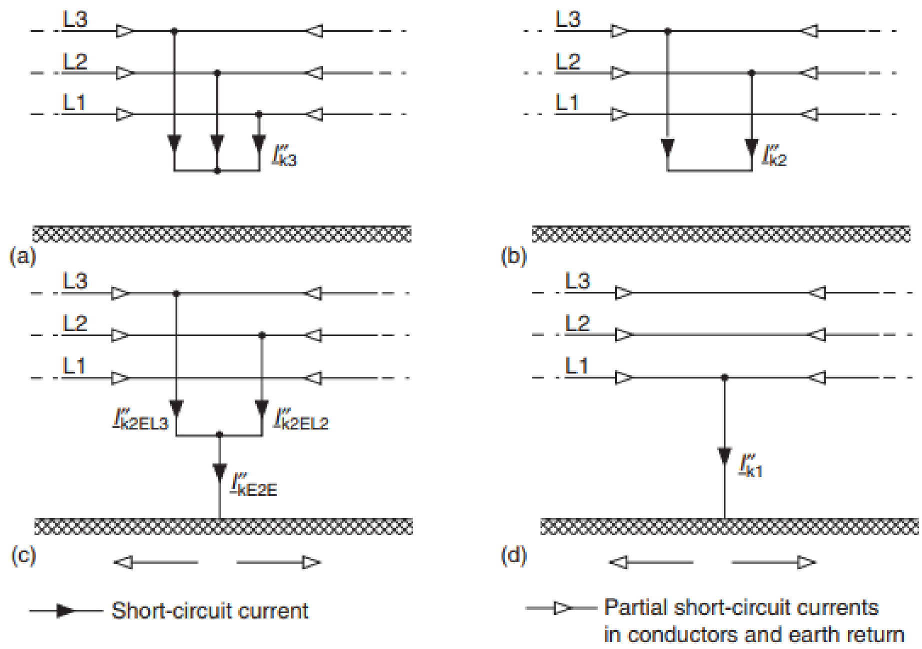


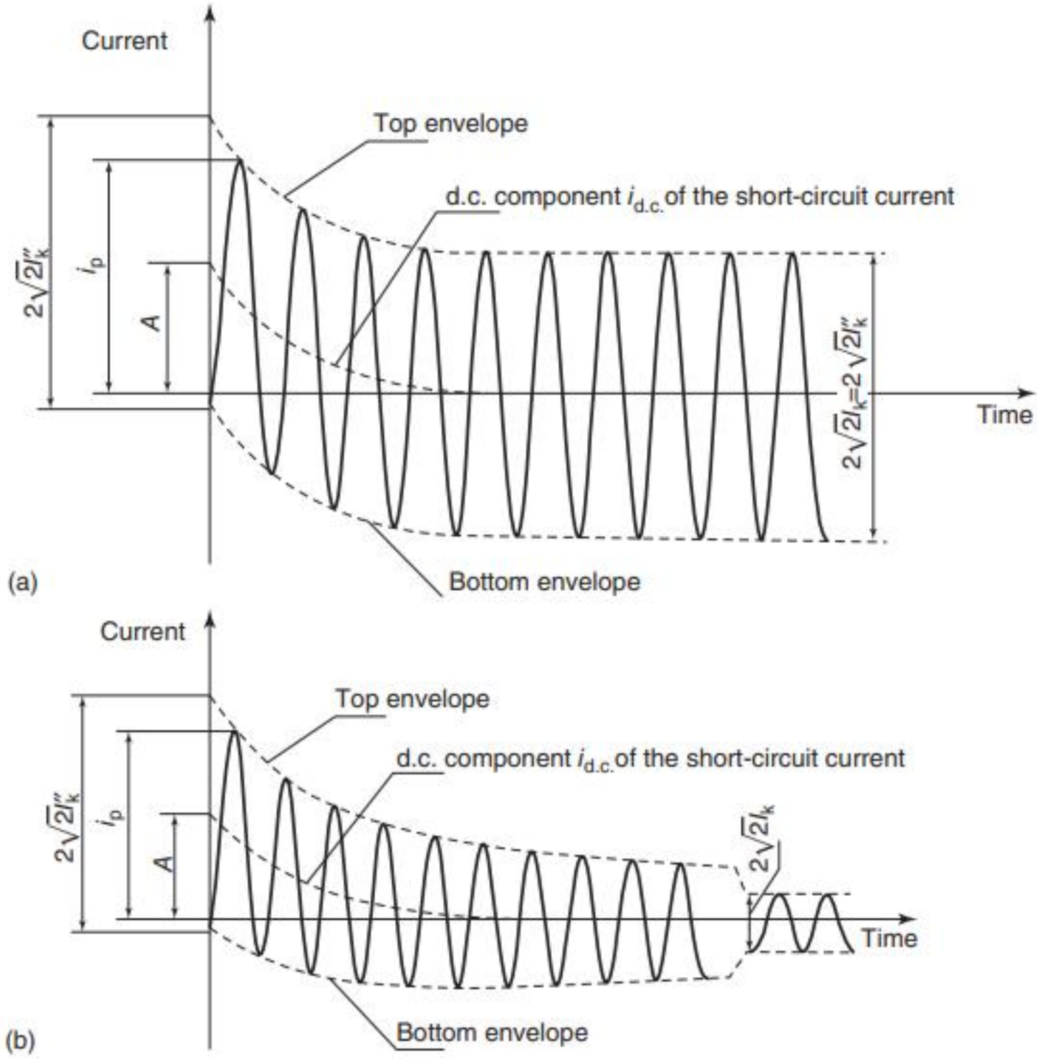
Figure 5.10 – Types of short-circuit currents in three-phase networks

The most common one is the single-phase grounded fault, which accounting for over 90 % of the total number of the faults.

The short-circuit causes passage of currents through the accidental or intentional connection making up the short-circuit itself and through the various components as far as the source: it is therefore a potential cause of damage and fires.

5.4.1 Time Behavior of the Short-Circuit Current

Figure 5.11 shows the time behavior of the short-circuit current for the occurrence of far-from-generator and near-to-generator short circuits. The d.c. aperiodic component depends on the point in time at which the short circuit occurs. For a near-to-generator short circuit, the sub-transient and the transient behaviors of the synchronous machines are important. Following the decay of all transient phenomena, the steady state sets in.



(a) Far-from-generator short circuit and (b) near-to-generator short circuit. $I_k^{''}$: initial symmetrical short-circuit current; i_p : peak short-circuit current; $i_{d.c.}$: decaying d.c. aperiodic component; and A: initial value of d.c. aperiodic component.

Figure 5.11 – Time behavior of the short-circuit current.

For the far-from-generator short circuit, the short-circuit current is, therefore, made up of a constant a.c. periodic component and the decaying d.c. aperiodic component. From the simplified calculations, we can now reach the following conclusions:

1) The short-circuit current always has a decaying d.c. aperiodic component in addition to the stationary a.c. periodic component.

2) The magnitude of the short-circuit current depends on the operating angle of the current. It reaches a maximum at γ =90° (purely inductive load). This case serves as the basis for further calculations.

3) The short-circuit current is always inductive.

5.4.2 Equivalent Voltage Source Method

The measurement or calculation of short-circuit current in LV networks on final circuits is very simple. In meshed and extensive power plants, the calculation is more difficult because of the short-circuit current of several partial short-circuit currents in conductors and earth return.

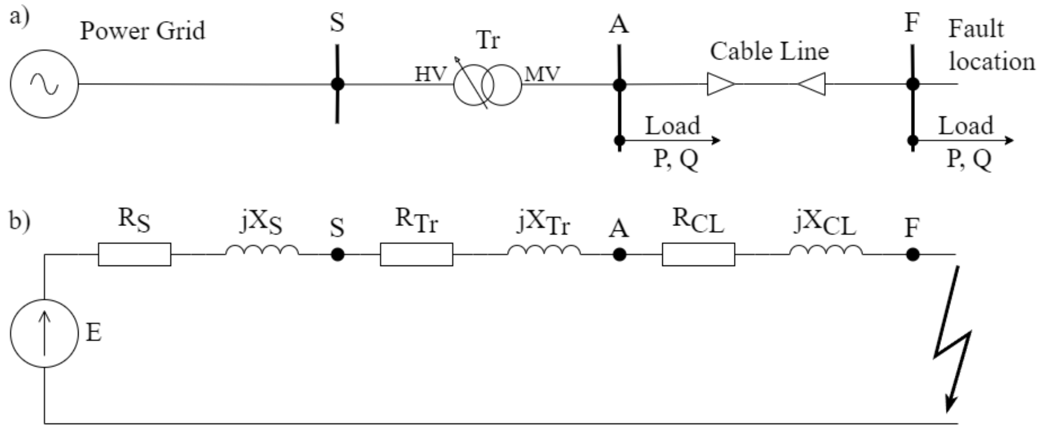
The short-circuit currents in three-phase systems can be determined by three different calculation procedures:

1) superposition method for a defined load flow case;

2) calculating with the equivalent voltage source E at the fault location; and

3) transient calculation.

The most common variant is Equivalent voltage source. Figure 5.12 shows an example of the equivalent voltage source at the short-circuit location *F* as the only active voltage of the system fed by a transformer with or without an on-load tap changer. All other active voltages in the system are short-circuited. Thus, the network feeder is represented by its internal impedance, Z_S, transferred to the LV side of the transformer and the transformer by its impedance referred to the LV side. The shunt admittances of the line, the transformer, and the nonrotating loads are not considered. The impedances of the network feeder and the transformer are converted to the LV side.



(a) System diagram and (b) equivalent circuit diagram of the positive-sequence system

Figure 5.12 – Network circuit with equivalent voltage source

The input is from a network, usually designated "*S*" for source, and not from a generator. The internal impedance of short circuit positive-sequence of a high-voltage (HV) network or a medium-voltage (MV) network can then be determined according to the following equation:

$$\underline{Z_Q} = R_Q + jX_Q \tag{5.4}$$

where R_Q – resistance of power supply feeder;

X_Q – reactance of power supply feeder.

Table 5.3 – Equivalent voltage source

Voltage source	E, p.u.
Turbogenerators	1.08÷1.13
Hydrogeneretors	1.13÷1.18
Synchronous compensator	1.2
Synchronious machine	1.1
Asynchronous machine	0.9
Power Grid	1
Load	0.85

Invertor is not included into Table 5.3 because of directly related to the network-connected generators are modeled simply by their sub-transient synchronous reactance. Short-circuit currents in generators with inverters and PV systems are modeled as voltage-controlled current sources. The currents injected in these investments are limited to the rated current and do not contribute, or only marginally, for a short-circuit current that must be specified by manufacturers.

Photovoltaic Power Plant is case of far-from-generator short circuit, so impedance of short circuit positive-sequence determined according as:

$$\underline{Z_Q} = 0 + jX_Q \tag{5.5}$$

5.4.3 Transformation of the Network Types Described to Equivalent Circuit Diagrams

There are many possible arrangements of networks. In order to calculate the total impedance at the position of the short circuit, the network topologies in multiple and meshed networks are simplified and transformed.

With this approach, the network is reduced to a network with simple inputs. The entire short-circuit path is represented by resistances and reactances, and the impedance at the position of the short circuit calculated from these.

The magnitude of the impedance is given by:

$$Z = \sqrt{R^2 + X^2} \tag{5.6}$$

According to formulae (5.5), rewrite the magnitude of the impedance:

$$Z = \sqrt{0 + X^2} = X \tag{5.7}$$

In next calculation will use (according to formulae (5.7)) only reactance *X*. The following relationships then apply:

- Series connection (Figure 5.13):

$$X_{total} = \sum_{i=1}^{n} X_i \tag{5.8}$$

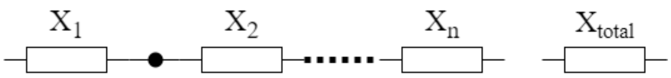


Figure 5.13 – Series connection

- Parallel connection (Figure 5.14):

$$\begin{cases} X_{total} = \dfrac{X_i}{n}, \quad when \;\; X_1 = X_2 = ... = X_n \\ \dfrac{1}{X_{total}} = \dfrac{1}{X_1} + \dfrac{1}{X_2} + ... + \dfrac{1}{Xn}, \quad when \;\; X_1 \neq X_2 \neq ... \neq X_n \end{cases} \tag{5.9}$$

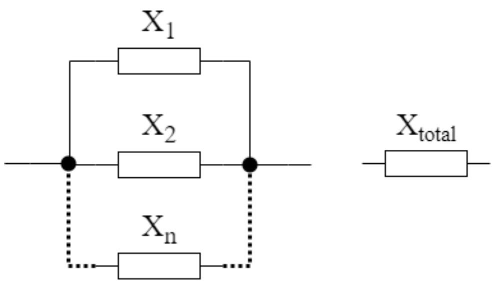


Figure 5.14 – Parallel connection

5.4.4 Components of Equivalent scheme

The calculation of short-circuit currents is based on the use of equivalent circuits for the operational equipment. In principle, the equivalent resistances and reactance must be determined for all equipment. The impedances of network transformers should take account of the impedance corrections for calculating the short-circuit currents. For transformers the reactance is given in the per unit (*pu*) or in the *%/MVA* system. Cables and lines are, however, assigned *Ω/km* values.

First of all, we choose the S_{basis} equal to highest capacity of electrical element, after that we calculate the reactance of transformers (*T*), the lines (*L*), and the power system (*S*).

5.4.4.1 Reactance of the transformer

The reactance of transformer calculates as following:

$$X_{Tr} = \frac{S_{basis}}{S_{r.Tr}} \cdot \frac{u_{SC}\%}{100\%} \tag{5.10}$$

where $S_{r.Tr}$ – rated power of transformer, *kVA*;

$u_{SC}\%$ – percentage of transformer short circuit voltage.

5.4.4.2 Reactance of the transmission lines and cables

The formula for lines and cables reactance is:

$$X_l = \frac{1}{n} \cdot x_{sp} \cdot l \cdot \frac{S_{basis}}{U_n^2} \tag{5.11}$$

where n – number of lines or cables;

x_{sp} – resistivity of transmission line or cable, *Ω/km*;

l – length of transmission line or cable, *km*;

U_n – voltage of transmission line or cable, *kV*.

Table 5.4 – The value of transmission lines and cables, x_{sp}, according to the voltage

Type of connection	x_{sp}
Transmission line:	
6–220 kV	0.4
Cable line:	
1–10	0.08
35	0.12

5.4.4.3 Reactance of the connection with Power Grid (System)

The formula for system reactance is:

$$X_s = \frac{S_{basis}}{S''} \tag{5.12}$$

where S'' – sub-transient power of connected system (Power Grid), Table 5.5, *VA*.

Table 5.5 – Sub-transient power average data according to voltage level

Volage level, *kV*	Sub-transient power S'', *kVA*
6.3 (7.4)	2 500 ÷ 16 000
10 (13.5-24)	25 000 ÷ 63 000
35 (34.5)	80 000÷1 000 000
110	1 000 000 ÷ 2 000 000

5.4.5 Calculation of short circuit current components

To start calculating of short circuit current components need simplified equivalent scheme (Figure 5.15) to result EMF and resistance, according to previous descriptions.

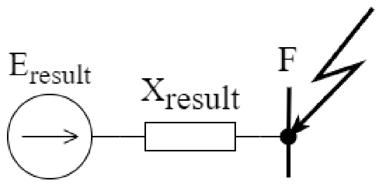


Figure 5.15 – Result simplified scheme

Effective value of **the periodic component** of the three-phase short circuit current at point F, *kA*:

$$I''_k = \frac{E_{result}}{X_{result}} \cdot \frac{S_{basis}}{\sqrt{3} \cdot U_n} \tag{5.13}$$

The peak value is calculated at the half cycle of the short-circuit condition. The exact time depends on the preload conditions and the time constants.

The peak current is calculated as, *kA*:

$$i_p = \sqrt{2} \cdot I''_k \cdot k_p \tag{5.14}$$

where k_p – peak coefficient of resulting equivalent scheme, depend on time constant of reducing of aperiodic d.c. short circuit component T_a.

Table 5.6 – Time constant of reducing of aperiodic d.c. short circuit component T_a and peak coefficient of resulting equivalent scheme k_p

Scheme part	T_a, seconds	k_p
System connected to Fault location by Transmission Line with voltage level, kV:		
<35	0.01	1.369
35	0.02	1.608
110–150	0.02–0.03	1.608–1.717
System connected to Fault location through transformer with rated power, *MVA*:		
80<	0.06–0.15	1.85–1.935
32–80	0.05–0.1	1.82–1.904
5.6–32	0.02–0.05	1.6–1.82
<5.6	0.005-0.02	1.4–1.6

The aperiodic d.c. component of short circuit current is calculated as follow, *kA*:

$$i_A = \sqrt{2} \cdot I''_k \cdot e^{-\tau / T_a} \tag{5.15}$$

where T_a – time constant of reducing of aperiodic d.c. short circuit component (Table 5.6);

τ – moment of time, determine by starting of disconnecting power contacts of breaker (≈0.03 *ms*) plus time of relay protection reactions (≈0.01 *ms*), taking equal to 0.04 *ms*.

Effective value of **the periodic component at moment of time τ**, *kA*:

$$I_{k\tau} = \gamma \cdot I''_k \tag{5.16}$$

where γ – typical curves of generator type base on relation of I''_k to start moment type I_{k0}.

In case of Photovoltaic Power Plant is far-from-generator (Figure 5.11), that is why formulae (5.16) transform to:

$$I_{k\tau} = I''_k \tag{5.17}$$

The last component is thermal impulse of the three-phase short-circuit current (B_k), kA^2sec, using the equation:

$$B_k = I''_k \cdot \left(t + T_a\right) \tag{5.18}$$

where t – time of action of short circuit, taking equal to 0.05 *sec*.

Self-testing questions for Chapter 5

1) What is the nominal voltage range typically used for switchgear in the MV electric network of a solar PV plant?
2) How is the reactance of the connection with the power grid calculated in the PV plant system?
3) Why is it not advisable to use machines with fans or oil circulators in substations for PV plants?
4) How is the reactance of a transformer calculated in the PV plant system?
5) What units are typically used to express the reactance of cables and lines in the PV plant network?
6) What are some factors to consider when determining the reactance of transmission lines and cables in a PV plant system?
7) What are some scenarios that should be considered when analyzing fault conditions in a PV power plant?
8) How does the formula for calculating short-circuit current components change when a PV power plant is far from the generator?
9) What is the significance of the thermal impulse of the three-phase short-circuit current in the context of PV plant design?
10) How can the design of the MV electric network impact the overall performance and efficiency of a solar PV plant?

6 SELECTING OF MAIN COMMUTATION EQUIPMENT

All elements of the switchgear of the electric station must work reliably under long-term normal conditions, as well as have sufficient thermal and dynamic stability during the most difficult short circuits. The reliability of the devices is guaranteed by the manufacturer only in case of their correct selection. When choosing devices, the compliance of their parameters with long-term working and short-term emergency modes that may occur during operation is checked. The main parameters of the equipment, which must meet the conditions of the working (long-term) mode, are the **nominal** *long-term current* ($I_{\max}$, *A*) and *voltage* (U_{rated} , *kV*) at level where we provide selecting.

Rated voltage is knowing, but nominal current is needed to calculate according to level where we provide selection:

- On Transmission Line 35 *kV*, $I_{\max}$, *A*:

$$I_{\max} = \frac{P_{TC}}{\sqrt{3} \cdot U_{rated} \cdot \cos\varphi} \tag{6.1}$$

where P_{TC} – power of transmission capacity of transmission line, Table 5.2, *kW*;

$\cos\varphi$ – the ratio of actual power to apparent power, for power plant with DC-AC converter can be take equal to 1.

- On Transmission Line 110 *kV*, $I_{\max}$, *A*:

$$I_{\max} = \frac{P_{TC}}{\sqrt{3} \cdot U_{rated} \cdot \cos\varphi \cdot K} \tag{6.2}$$

where K – coefficient of current distribution unevenness, for 110 *kV* transmission line equal to 0.7.

- On Transformer, $I_{\max}$, *A*:

$$I_{\max} = \frac{S_{Tr}}{\sqrt{3} \cdot U_{rated}} \tag{6.3}$$

where S_{Tr} – full power of transformer, *kVA*.

After that, the devices are **checked according to the parameters of the short-circuit mode**. A three-phase short-circuit is taken as the calculation type, as type with highest level of short circuit parameters. Electrodynamic stability is characterized by the maximum permissible current of the device, which must be equal to or greater than the calculated peak current i_p. Checking the devices for thermal stability consists in comparing the calculated thermal pulse with the product of the square of the nominal current of the thermal stability of the device and the nominal time of thermal stability, which is indicated in the catalog. IEC allows not to check the thermal resistance of conductors and devices protected by fuses.

The IEC prescribes selecting bus disconnectors, circuit breakers, measured current and voltage transformers, and current-conducting parts, flexible busbars.

During the selection of current-conducting parts according to the conditions of the operating mode, two factors are taken into account: the heating of the conductor by long-term operating current and the requirement for the efficiency of the installation. When choosing the cross-sections of conductors according to the conditions of the duration of heating, tables of permissible continuous currents for conductors of standard cross-sections, compiled on the basis of relevant calculations and experiments, are used.

6.1 Circuits-breakers

Circuit-breakers are **selected** according to main nominal parameters:

- by voltage:

$$U_{rated} \leq U_{nom} \tag{6.4}$$

where U_{nom} – nominal voltage of circuit-breaker, *kV*.

- by long-term current:

$$I_{\max} \leq I_{nom} \tag{6.5}$$

where I_{nom} – nominal current of circuit-breaker, *A*.

Table 6.1 – Indoor circuit-breakers, vacuum type

Parameter	Type of circuit-brekers						
	VR-0	VR-1	VR-2	VR-3	VR-6	VR-6K	VR-6B
U_{nom}, kV	10/12	10/12	10/12	10/12	6/7.2	6/7.2	6/7.2
I_{nom}, A	630, 800	630-1250	630-1600	2000-3150	1600, 2000	1600, 2000	1600-3150
$I_{br.c}$, kA	12.5	20	20, 31.5	40	40	40	40
i_{rp}, kA	32	52	52, 80	102	128	102	128
I_T, kA	12.5	20	20, 31.5	40	40	40	40
t_T, sec	3						
I_{MC}, kA	12.5	20	20, 31.5	40	40	40	40

Table 6.2 – Outdoor circuit-breakers, SF_6 type

Parameter	Type of circuit-brekers			
	SF-35/1	SF-35/2	SF-110/1	SF-110/2
U_{nom}, kV	34.5/35	34.5/35	110/126	110/126
I_{nom}, A	1600	1600	2000	2000
$I_{br.c}$, kA	31.5	36/40	40	40/50
i_{rp}, kA	52/80	52/80	102	128
I_T, kA	31.5	36/40	40	40/50
t_T, sec	3			
I_{MC}, kA	31.5	36/40	40	40/50

Circuit-breakers are **checked** by breaking capacity of symmetrical current, aperiodical d.c. component, electrodynamic and thermal stability, according to the previously calculated short-circuit current (paragraph 5.4):

- By breaking capacity of symmetrical current by condition:

$$I_{k\tau} \le I_{br.c} \tag{6.6}$$

where $I_{k\tau}$ –the periodic component of short circuit current, formulae (5.13), kA;

$I_{br.c}$ – the breaking capacity of circuit-breaker, kA.

- By breaking capacity of aperiodic d.c. component of short circuit current by condition:

$$i_A \leq i_{Anom} \tag{6.7}$$

where i_A–the aperiodic d.c. component of short circuit current, formulae (5.15), *kA*;

i_{Anom} – the nominal allowed value of aperiodic d.c. component of short circuit current, which breaking off at period of time τ (moment of time, determine by starting of disconnecting power contacts of breaker at datasheet plus time of relay protection reactions ≈0.01 *ms*), *kA*:

$$i_{Anom} = \frac{\sqrt{2} \cdot \beta_n \cdot I_{br.c}}{100} \tag{6.8}$$

where β_n –the normalized value of the content of the aperiodic component in the short-circuit current, %, which is determined by the curve shown in Figure 6.1, *pu*:

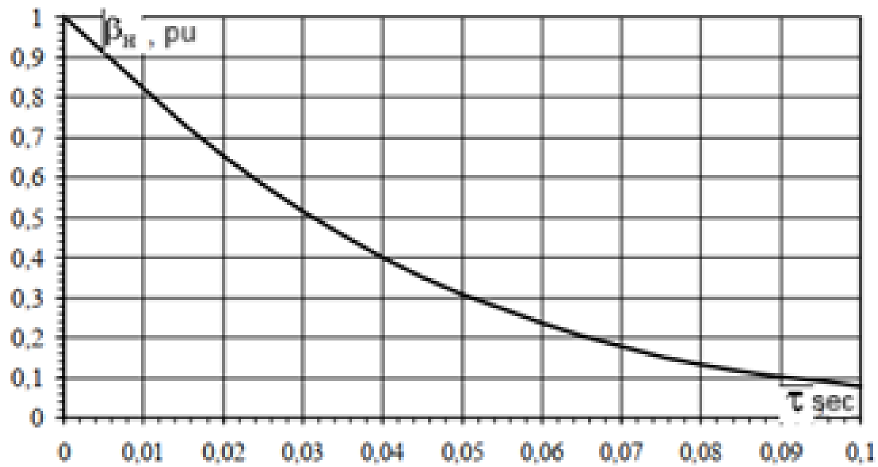


Figure 6.1 – The normalized relative value of the aperiodic component in the short-circuit current

As alternative β_n can be calculated by formulae:

$$\beta_n \approx e^{-\tau/0.045} \tag{6.9}$$

In case when $I_{k\tau} \leq I_{br.c}$ condition is fulfilled, but $i_A \leq i_{Anom}$ is not, it possible additionally checked by breaking capacity of full current:

$$\left(\sqrt{2} \cdot I_{k\tau} + i_A\right) \leq \sqrt{2} \cdot I_{br.c} \cdot \left(1 + \frac{\beta_n}{100}\right) \tag{6.10}$$

- By electrodynamic stability, according to limit thought out short circuit currents

$$\begin{cases} I''_k \leq I_{MC} \\ i_p \leq i_{rp} \end{cases} \tag{6.11}$$

where I_{MC} – the making current of circuit breaker, *kA*;

i_{rp} – rated peak withstands current of circuit breaker, *kA*.

- By thermal stability B_k, according to thermal impulse of short circuit current, kA^2t:

$$B_k \leq I_T^2 \cdot t_T \tag{6.12}$$

where I_T – the rms value of the short circuit current withstand duration (thermal resistance current) according to the catalog (Rated short circuit breaking current), *kA*;

t_T – withstand duration of thermal resistance current according to the catalog (rated short-time withstand duration), *sec*.

6.2 Disconnectors

Disconnectors are **selected** according to main nominal parameters:

- by voltage:

$$U_{rated} \leq U_{nom} \tag{6.13}$$

where U_{nom} – nominal voltage of disconnector, *kV*.

- by long-term current:

$$I_{\max} \leq I_{nom} \tag{6.14}$$

where I_{nom} – nominal current of disconnector, *A*.

Table 6.3 – Outdoor disconnectors

Parameter	Type of diskonectors			
	D-35/1	D-35/2	D-110/1	D-110/2
U_{nom}, *kV*	34.5/35	34.5/35	110/126	110/126
I_{nom}, *A*	1600	1600	2000	2000
i_{rp}, *kA*	80	102	128	140
I_T, *kA*	31.5	36/40	40	40/50
t_T, sec	3			

Disconnectors has easier checked procedure in compere to circuit breaker because disconnectors are not adapted to disconnect either normal or, even more so, emergency currents. That is why disconnector checked only by electrodynamic and thermal stability, according to the previously calculated short-circuit current (paragraph 5.4):

- By electrodynamic stability, according to limit thought out short circuit currents

$$i_p \leq i_{rp} \tag{6.15}$$

where i_{rp} – rated peak withstands current of disconnector, *kA*.

- By thermal stability B_k , according to thermal impulse of short circuit current, kA^2t:

$$B_k \le I_T^2 \cdot t_T \tag{6.16}$$

where I_T – the rms value of the short circuit current withstand duration (thermal resistance current) according to the catalog (Rated short circuit breaking current), *kA*;

t_T – withstand duration of thermal resistance current according to the catalog (rated short-time withstand duration), *sec*.

6.3 Measured transformers

6.3.1 Measured current transformers

Measured current transformers are **selected** according to main nominal parameters:

- by voltage:

$$U_{rated} \le U_{nom} \tag{6.17}$$

where U_{nom} – nominal voltage of disconnector, *kV*.

- by long-term current:

$$I_{\max} \le I_{nom} \tag{6.18}$$

where I_{nom} – nominal current of disconnector, *A*.

The nominal current should be as close as possible to the operating current of the installation, because the underloading of the primary winding leads to an increase in measurement errors.

- By design and accuracy class:

According to the design, there are current transformers: coil, single-turn, multi-turn with molded insulation. Multi-turn transformers with cast insulation are intended for indoor switchgear and are structurally compatible with one of the plug connectors of the primary circuit of the cell. For large currents, busbar transformers are used, in which the role of the primary winding is played by the busbar. For outdoor switchgear, they produce transformers in a porcelain case with paper-oil insulation and of the cascade type. Built-in current transformers are installed on the terminals of oil tank circuit breakers and power transformers with a voltage of 35 kV and above.

The accuracy class of current transformers according to IEC 60044-8 is chosen according to their purpose.

Table 6.4 – Measured current transformers

Parameter	CT-6	CT-10	CT-35	CT-110
U_{nom}, kV	6/7.2	10/12	34.5/35	110/126
I_{nom}, A	1200	1200	1600	2000
$I_{secondary}$, A	1, 5	1, 5	1, 5	1, 5
The accuracy class	0.2, 0.5, 10	0.2, 0.5, 10	0.2, 0.5, 10	0.2, 0.5, 10
Secondary load, at *cosφ*=0.8, *VA*	30, 50	30, 50	30	30
K_p	25			
I_T, kA	25	25	40	40
t_T, sec	3			

Measured current transformers **checked** by electrodynamic and thermal stability, according to the previously calculated short-circuit current (paragraph 5.4), and by secondary load:

- By electrodynamic stability, according to limit thought out short circuit currents:

$$\begin{cases} i_p \le K_p \cdot \sqrt{2} \cdot I_{1nom} \\ i_p \le i_{rp} \end{cases} \quad (6.19)$$

where K_p – multiplicity of electrodynamic stability according to the catalogue of current transformer;

I_{1nom} – rated primally current of current transformer, A;

i_{rp} – rated peak withstands current of current transformer, kA.

- By thermal stability B_k, according to thermal impulse of short circuit current, kA^2t:

$$\begin{cases} B_k \le \left(K_p \cdot I_{1nom}\right) \cdot t_T \\ B_k \le I_T^2 \cdot t_T \end{cases} \tag{6.20}$$

where K_p – multiplicity of thermal stability according to the catalogue of current transformer;

I_T – thermal resistance current, according to the catalog of current transformer, *kA*;

t_T – withstand duration of thermal resistance current, according to the catalog of current transformer, *sec*;

I_{1nom} – rated primally current of current transformer, *A*.

- By secondary load, Z_2:

$$Z_2 \le Z_{2nom} \tag{6.21}$$

where Z_{2nom} – nominal permissible load of the current transformer in the selected accuracy class.

$$Z_2 = r_2 + jx_2 \tag{6.22}$$

where x_2 – reactive resistance of current circle, the inductive resistance is small, that is why it takes equal to 0, and $Z_2 \approx r_2$;

r_2 – active resistance of current circle, consist of resistance of connection wires r_w, transient resistance of contact elements r_c and resistance of apparatus r_{ap}:

$$r_2 = r_{ap} + r_w + r_c \tag{6.23}$$

Resistance of apparatus r_{ap}, calculate as:

$$r_{ap} = \frac{S_{ap}}{I_2^2} \tag{6.24}$$

where S_{ap} – power which consume by all connected apparatus, *VA*;

I_2 – secondary nominal current, according to the catalog of current transformer. *A*.

To calculate sum of power $\left(S_{ap}\right)$ which consume by all connected apparatus is recommended to use table form (Table 6.5).

Table 6.5 – Calculation of sum of power which consume by all connected apparatus

Name and type of apparatus	Phase ***A***	Phase ***B***	Phase ***C***
Amperemeter	0.1	0.1	0.1
Electric energy meter	2.5	–	2.5
…	…	…	…
Sum:	…	…	…

Current transformers are installed in all sections (sections of transformers, lines, etc.). It is also necessary to take into account the schemes of inclusion and distribution of devices by sets of current transformers (Table 6.6).

Contact resistance r_c is taken as 0.05 Ohms if 2-3 devices are included in the circuit, and 0.1 Ohms for more devices.

Knowing Z_{2nom}, we determine the permissible resistance as:

$$r_w = Z_{2nom} - r_{ap} - r_c \tag{6.25}$$

And needed to calculate cross-section of this wires. Cross-section must be more than 2.5 mm^2 for cooper and 1.5 mm^2 for aluminum, and less than 6 mm^2. Calculated as:

$$q = \rho \cdot \frac{l_{calc}}{r_w} \tag{6.26}$$

where ρ – resistivity constant of wire material (0.0175 for cooper, 0.0283 for aluminum);

l_{calc} – calculated length, depends of current transformer connection type and distance to aparatures.

Table 6.6 – Measuring devices that must be installed in a concrete electrical circuit

Part of Electrical Circle	Place of installing	List of apparatures
Transformer of connection with Power Grid	Two-windings	Amperemeter, Wattmeter, Varmeter with two side measured line
	Three-windings	Same as for two windings
Transmission Lines 35*kV*	–	Amperemeter, Energy meters of active and reactive power, Wattmeter.
Transmission Lines 110*kV*	–	Amperemeter, Energy meters of active and reactive power, Wattmeter, Varmeter, Appliance for detection of short circuit place
Busbar near source	At all busbar system or on each section	Voltmeter for between phases measuring, Voltmeter with switching for measuring three phases, Frequency counter, Appliance for synchronization: two frequency counters, two Voltmeters and synchronoscope.
Circuit-breakers	–	Amperemeter
Busbar 6-35 *kV*	At all busbar system or on each section	Voltmeter for between phases measuring, Voltmeter with switching for measuring three phases
Busbar 110 *kV*	At all busbar system or on each section	Voltmeter for between phases measuring and Register voltmeter, Scope, Appliance for register U_0

Calculated length in case: when current transformer connected into not full star $l_{calc} = \sqrt{3} \cdot l$; connected into full star $l_{calc} = l$; applied ito one phase $l_{calc} = 2 \cdot l$. Where l is taken length of different connections, *m*, (Table 6.7).

Table 6.7 – Length of different connections, *m*

Indoor switchgear 6–24 *kV*	25–60
Outdoor switchgear 35 *kV*	60–75
Outdoor switchgear 110 *kV*	75–100
Busbar	25–100

6.3.2 Measured voltage transformer

Measured voltage transformers are **selected** according to main nominal parameters:

- by voltage:

$$U_{rated} \le U_{nom} \quad (6.27)$$

where U_{nom} – nominal voltage of disconnector, *kV*.

- by configuration and scheme of winding connection.
- by accuracy class

Table 6.8 – Measured voltage transformers

Parameter	VT-6	VT-10	VT-35	VT-110
U_{nom}, *kV*	6/7.2	10/12	34.5/35	110/126
I_{nom}, *A*	1200	1200	1600	2000
$U_{secondary}$, *V*	100			
The accuracy class	0.2, 0.5, 10	0.2, 0.5, 10	0.2, 0.5, 10	0.2, 0.5, 10
Secondary load, at *cosφ*=0.8, *VA*	1500			
I_T, *kA*	25	25	40	40
t_T, sec	3			

Measured voltage transformers **checked** by secondary load:

$$S_{2\Sigma} \le S_{nom} \quad (6.28)$$

where S_{nom} – rated nominal power, in accordance to choose accuracy class, *VA*;

$S_{2\Sigma}$ – calculated sum of load of all measured appliance connected to voltage transformer, *VA*.

As for current transformer, to calculate load of voltage transformer recommended table form (Table 6.9).

Table 6.9 – Calculation voltage transformer load

Name and type of appliance	Power of one winding of appliance, *VA*	Number of windings	$\sin\varphi$	$\cos\varphi$	Active power *P*, *W*	Reactive power *Q*, *Var*
Voltmeter	2	1	0	1	2	–
Wattmeter	1.5	2	0	1	3	–
Energy meters	2	2	0,925	0,38	4	9,7
…	…	…	…	…	…	…
Sum:	…	…	…	…	…	…

Calculated sum of load $S_{2\Sigma}$, *VA*:

$$S_{2\Sigma} = \sqrt{P^2 + Q^2} \tag{6.29}$$

6.4 Selection of Cables

The cross-section of conductors is selected based on the economic current density for normal operating conditions. Cross-sections of lines at 0.2÷1 kV and above are determined based on the condition of minimal electrical energy losses, i.e., according to the economic current density, which is selected based on the conductor material and the duration of maximum load usage.

Cables select by:

- Voltage of mechanism:

$$V_m \le V_{nom} \tag{6.30}$$

- Cable characteristic, such as insulation type according to using condition.
- Economic cross-section density, *mm²*:

$$F_{ec} = \frac{I_{nom}}{J_{ec}} \tag{6.31}$$

where I_{nom} – nominal AC current of inverter, *A*;

J_{ec} – economic current density, according to Table 6.10, *A/mm²*.

Table 6.10 – Economic Current Density

Conductor	J_{ec}, mm2	
	Copper	Aluminum
Non-insulated wires and busbars	2,5	1,1
Cables with PVC insulated conductors	3,0	2,5
Cables with XLPE and LLDPE sheathing insulation	3,5	3,1

Cables selected in the normal mode are checked for thermal resistance according to the conditions:

- by permissible current, A:

$$I_{\max} \le I_{allow} \tag{6.32}$$

where I_{allow} – permissible current accordance to coefficients of mutual influence of the laid type in a row (f_1), and environment temperature (f_2).

$$I_{allow} = f_1 \cdot f_2 \cdot I_{allow.nom} \tag{6.33}$$

where $I_{allow.nom}$ – permissible current accordance to cross-section of chooses cable (Table 6.11 – for copper, Table 6.12 – for aluminum). In case when technical datasheet of power cables already has data about the laid type in a row it already takes the f_2 coefficient into account.

- by cross-section:

$$F_{nom} \ge F_{\min} \tag{6.34}$$

where F_{nom} – cross-section chooses from catalogue (Table 6.11, Table 6.12), according to economic cross-section density, mm^2;

$F_{\min}$ – minimal allowance cross-setion, according to thermal influence of short circuit, mm^2:

$$F_{\min} = \frac{\sqrt{B_k}}{C} \tag{6.35}$$

where C – constant function, accordance to cable material and voltage level (6 kV – aluminum is 98, cooper is 114; 10 kV – aluminum is 100, cooper is 118).

Table 6.11 – Technical data of copper cable

Type	Nominal Cross-sectional area, F_{nom}	Maximum Conductor Resistance AC at 70 °C	Current Rating					
			Laid in ground		Laid in free air (Shaded)			
			Flat	Trefoil	Duct	Flat Separated	Flat Touched	Trefoil Touched
	mm2	*Ohm/Km*	*A*	*A*	*A*	*A*	*A*	*A*
CP25	25	0,87	144	146	108	151	124	120
CP35	35	0,6272	173	175	131	185	151	147
CP50	50	0,4634	204	207	156	223	183	179
CP70	70	0,3212	249	253	192	280	230	224
CP95	95	0,2317	297	302	232	340	281	274
CP120	120	0,1841	337	343	265	392	325	317
CP150	150	0,1497	377	384	300	445	371	362
CP185	185	0,1203	425	433	343	509	427	416
CP240	240	0,0926	489	500	400	599	506	494
CP300	300	0,075	548	562	456	684	581	569
CP400	400	0,0601	615	633	523	779	669	656
CP500	500	0,0488	687	711	594	889	769	756
CP630	630	0,0402	761	791	671	1007	872	862
CP800	800	0,034	829	867	746	1121	978	970
CP1000	1000	0,0298	889	939	826	1236	1090	1088

Table 6.12 – Technical data of aluminum cable

Type	Nominal Cross-sectional area, F_{nom}	Maximum Conductor Resistance AC at 70 °C	Current Rating					
			Laid in ground		Laid in free air (Shaded)			
			Flat	Trefoil	Duct	Flat Separated	Flat Touched	Trefoil Touched
	mm²	*Ohm/Km*	*A*	*A*	*A*	*A*	*A*	*A*
AL16	16	2,2949	87	88	65	90	73	71
AL25	25	1,4419	112	113	84	118	96	94
AL35	35	1,043	134	136	101	144	117	114
AL50	50	0,7704	158	160	121	174	142	139
AL70	70	0,5326	194	197	150	218	179	174
AL95	95	0,385	231	235	180	265	219	213
AL120	120	0,3046	263	267	207	306	253	247
AL150	150	0,2483	294	299	233	348	289	281
AL185	185	0,1981	333	339	268	400	334	325
AL240	240	0,1517	385	392	314	472	397	387
AL300	300	0,1221	433	443	359	542	459	447
AL400	400	0,0959	493	505	417	626	535	523
AL500	500	0,0759	559	575	480	724	624	611
AL630	630	0,0606	630	651	549	833	721	708
AL800	800	0,0495	702	729	628	951	829	817
AL1000	1000	0,0417	770	806	709	1071	942	933

6.5 Flexible busbar (wires)

Flexible busbar (wires) is used to connect transformers to the outdoor switchgear. **Selection** same as for cables.

Wires of power transmission lines with a voltage of more than 35 kV, wires of long connections of block generators with outdoor are **checked** for economic current density according to formula (6.32). The section found by (6.31) is rounded to the nearest standard.

- The following are not subject to **checking** for economic current density: busbars of electrical installations and busbars within the limits of open and closed RUs of all voltages; networks of temporary structures, as well as devices with a service life of 3–5 years.

- **Checking** the section for heating (according to the permissible current) is carried out according to (6.32). The selected section is checked for the thermal effect of the short-circuit current according to (6.35). Splitting of wires of overhead lines when checking for heating under short-circuit conditions is considered as one wire of the total cross-section.

- The flexible busbars of the outdoor switchgear are **checked** for the electrodynamic action of the short-circuit current at $I''_k \geq 20\,kA$ and the wires of transmission lines at $i_p \geq 50\,kA$.

Table 6.13 – Technical data of aluminum wires

Product code	Cross-section	Number and nominal diameter of wires	Max. resistance	Rated strength	Approx. overall diameter	Approx. Weight	Current carrying capacity
	mm²	*Nox⌀*	*Ohm*	*KN*	*mm*	*Kg/km*	*Amp*
AA-16	16	7x1.7	2.07	4.69	5.1	43.4	105
AA-25	25	7x2.1	1.3566	7.15	6.3	66.2	135
AA-35	35	7x2.5	0.9572	10.14	7.5	93.8	170
AA-50.1	50	7x3	0.6647	14.6	9	135.1	210
AA-50.1	50	19x1.8	0.6841	14.26	9	132.7	210
AA-70	70	19x2.1	0.5026	19.41	10.5	180.7	255
AA-95	95	19x2.5	0.3546	27.51	12.5	256	320
AA-120	120	19x2.8	0.2827	34.51	14	321.2	365
AA-150	150	37x2.25	0.2256	43.4	15.8	405.3	425
AA-185	185	37x2.5	0.1827	53.58	17.5	500.3	490
AA-240	240	61x2.25	0.1373	71.55	20.3	670.3	585
AA-300	300	61x2.5	0.1112	88.33	22.5	827.5	670
AA-400	400	61x2.89	0.0832	118.04	26	1105.9	810
AA-500	500	61x3.23	0.066	147.45	29.1	1387.4	930
AA-625	625	91x2.96	0.0534	184.73	32.6	1737.7	1075
AA-800	800	91x3.35	0.0417	236.62	36.9	2225.8	1255
AA-1000	1000	91x3.74	0.0334	294.91	41.1	2774.3	1450

- With large short-circuit currents, the wires in the phases can become so close as a result of dynamic interaction that there will be a crossing or a breakdown between the phases. The greatest convergence of phases is observed with a two-phase short-circuit between adjacent phases, when the wires are first thrown in opposite directions, and then after the short-circuit current is turned off, they move toward each other. Their convergence will be greater, the shorter the distance between the phases, the greater the sag arrow and the greater the duration of the flow and the value of the short-circuit current.
- By flexible busbar (wire) displacement b, *m*. Determined by Figure 6.2 in depending of ratio $\frac{f}{g}$ and $\frac{\sqrt{h}}{t_{ec}}$. Where f is the force from the long-term current of short-circuit (*N/m*); g is gravitation force (*N/m*); h is the maximum design sag in each run at the maximum design temperature (*m*), not more than

2 – 2.5 *m* for outdoor switchgear; t_{ec} is pulse-equivalent action time of fast-acting protection (*sec*), takes equal to 0.15 *sec*.

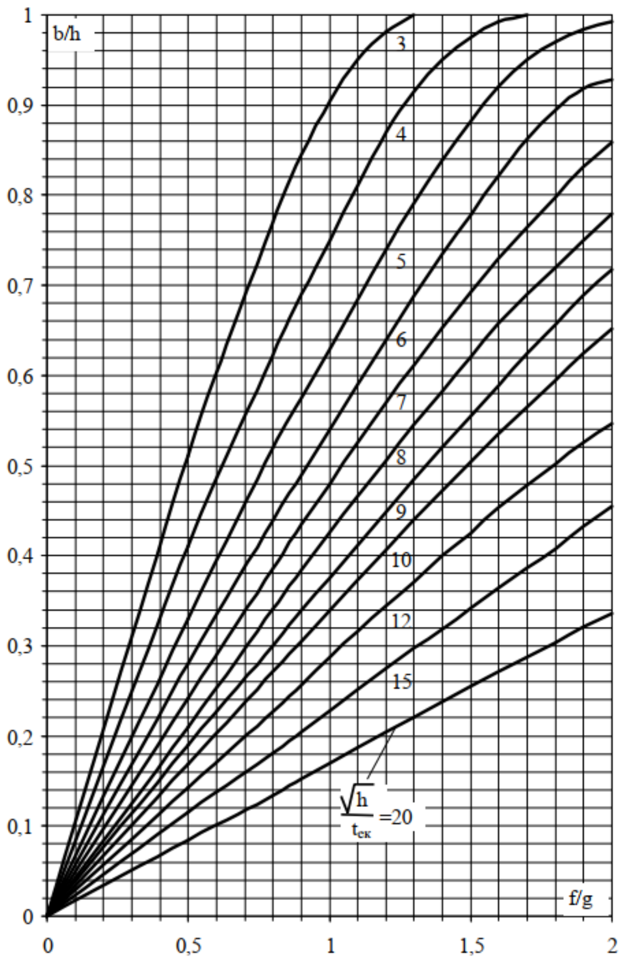


Figure 6.2 – Displacement diagram of a flexible current conductor with horizontal arrangement of phases under the action of short-circuit currents

Found displacement b compare with maximal acceptable b_{ac}:

$$b < b_{ac} = \frac{D - d - a_{ac}}{2} \qquad (6.36)$$

where D – distance between phases (Table 6.14), *m*;

d – diameter of flexible busbar (wire), *m*.

The force from the long-term current of short-circuit is determined, *N/m*:

$$f = 0.15 \cdot \frac{\left(I_k''\right)^2}{D} \tag{6.37}$$

Table 6.14 – Parameters D and a_{add}

Parameter	Flexible busbar (wires) of outdoor switchgear, *kV*	
	35	110
D, m	1.5	3
a_{add}, *m*	–	0.45

Gravitation force on 1 *m* of flexible busbar (wires), *N/m*:

$$g = 9.8 \cdot m \tag{6.38}$$

where *m* – weight for 1 *m*.

If it turns out that $b > b_{ac}$, then it is necessary to reduce the sag arrow or increase the distance between the phases. In practice, in some cases, install transverse insulating spacers, which allows not to increase the distance between phases and not to reduce the sag arrow. When, after all, it is necessary to reduce the sag boom, install additional supports, that is, the span is actually reduced.

- Flexible busbars (wires) with split phases are also checked for electrodynamic interaction of conductors of one phase.

The force on each wire from the interaction with the remaining n-1 wires, *N/m*:

$$f_c = \frac{n-1}{n^2} \cdot 0.2 \cdot \frac{\left(I_k''\right)^2}{d} \tag{6.39}$$

where n – number of wires at each phase.

Under the action of impulse forces f_c, the conductors tend to get closer to the center. To fix the wires and reduce impulse forces, in-phase (distance) spacers are installed in them.

- Corona testing is required for flexible conductors with a voltage of 35 *kV* and above. A discharge in the form of a corona occurs near wires at high electric field intensities. Air ionization processes near the wire lead to additional energy losses, to the occurrence of radio interference and the formation of ozone, which negatively affects the contact surfaces. Check as comparison between initial critical intensity E_0 and electric field strength E (maximum value):

$$1{,}07 \cdot E \le 0.9 \cdot E_0 \qquad (6.40)$$

A discharge in the form of a corona occurs at the maximum value of the initial critical intensity of the electric field, *kV/cm*:

$$E_0 = 30.3 \cdot m \cdot \left(1 + \frac{0.299}{\sqrt{r_0}}\right) \qquad (6.41)$$

where m – coefficient that takes into account the roughness of the wire surface, equal 0.82;

r_0 – wire radius, *cm*.

Electric field strength (maximum value) near the surface of unsplit or near split wires, *kV/cm*:

$$E = K \cdot \frac{0.354 \cdot U_{max}}{n \cdot r_0 \cdot \lg \dfrac{D_{av}}{r_{ek}}} \qquad (6.42)$$

where K – coefficient that takes into account the number of wires in a phase;

U_{max} – maximum permissible installation voltage, *kV*;

n – number of wires at each phase;

D_{av} – the average geometric distance between the phase wires, cm (with the horizontal arrangement of the phases $D_{av} = 1.26 \cdot D$);

r_{ek} – equivalent radius of split wires, cm (Table 5.4).

Table 6.15 – Parameters K and r_{ek}

Parameter	number of wires at each phase			
	1	2	3	4
K	1	$1 + 2 \cdot \frac{r_0}{a}$	$1 + 2 \cdot \sqrt{3} \cdot \frac{r_0}{a}$	$1 + 3 \cdot \sqrt{2} \cdot \frac{r_0}{a}$
r_{ek}	r_0	$\sqrt{r_0 \cdot a}$	$\sqrt[3]{r_0 \cdot a^2}$	$\sqrt[4]{\sqrt{2} \cdot r_0 \cdot a^3}$

The distance between the wires in the split phase a is taken 1 for outdoor switchgear less than 110 *kV*.

Self-testing questions for Chapter 6

1) What is the formula for calculating the withstand duration of a thermal resistance current?

2) By what parameters are measured current transformers selected?

3) What are the different types of current transformers?

4) How is the load of a voltage transformer calculated in relation to the power of connected appliances?

5) What factors are considered when selecting the cross-section of conductors for cables in an electrical installation?

6) Why are in-phase spacers installed in conductors, and when is corona testing required?

7) How is the resistance of apparatus, connected to measured transformers, calculated?

8) What measuring devices must be installed in a concrete electrical circuit according to installing place?

9) How is the permissible resistance determined based on the rated nominal impedance?

10) What are the criteria for calculating the cross-section of wires in terms of material and size limitations?

7 DRAWING PART

Based on the calculations of the previous chapters, data are obtained to finalize the materials. Namely, you depict the Main Electrical Diagram of a Solar Photovoltaic Power Plant. Which includes a part of DC and AC.

The DC part of the circuit includes a schematic representation of the selected equipment in Chapters 3 and 4. Namely (Table 7.1):

- Photovoltaic panels
- Inverter(s)
- Combiner boxes (if equipped)
- Recombiner boxes (if equipped)
- DC Cable Lines
- String fuses
- Array fuses (if equipped)
- Switch-Disconnectors (if equipped)

The part of the circuit that displays AC includes a schematic representation of the selected equipment from Chapters 5 and 6. Namely (Table 7.2):

- Power Transformer(s)
- Power Transmission Line of communication with the power grid
- Circuit-breaker(s)
- Disconnectors
- AC Cables Lines
- Measuring Current and Voltage Transformer(s)
- Flexible bus (if equipped)
- Solid bus (if equipped)

Next to each element shown, there should be a descriptive part next to it – a schematic name (numbered alternately), indicate the type (if a choice was made), power, explanatory text of the element (if there is a need to indicate a certain feature, for example, by installation).

Text on drawing mut be next sizes: For Headers – 7 mm, for base text – 3.5 mm

Table 7.1 – DC elements

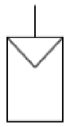
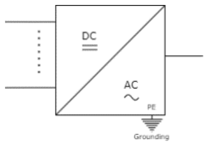
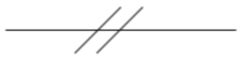
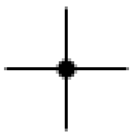
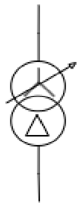
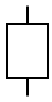
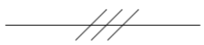
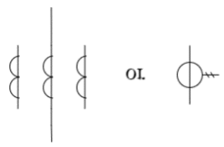
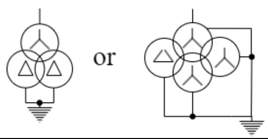
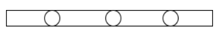
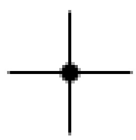
Name of element	Schematic name	Schematic view	Indicate text example	Note
Photovoltaic panels	PV		PV 1 SIL- 300 300 W	*Dimensions is 20x10 mm*
Invertor	Inv		Inv 1 PVS-175-TL 175 kW	*Dimensions is 30x30 mm Can be rotate vertically*
Combiner box	Cb		Cb 1 Combine 9 strings	*Shown as highlight area of string combining, inside has fuses*
Recombiner box	Rb		Rb 1 Combine 5 Cb	*Shown as highlight area of arrays combining, inside has fuses*
DC cable	–		Al-2.5, 1.5 kV, 2 cables	*Shown as solid line, with graphical showing of cables number*
Fuse	–		F20A	*Rectangular of fuse has dimensions 4x10*
Switch-Disconnector	SD		SD1 PVS-175-TL	*Circle of connection has dimension Ø2mm, and line of contact is 10 mm*
Connection point	–		–	*In place where need to show electrical connection it is shown as dot with diameter Ø3 mm*

Table 7.2 – AC elements

Name of element	Schematic name	Schematic view	Indicate text example	Note
Power Transformer	*T*		*T1* *ST-1000*	*Circle has dimension Ø20 mm*
Transmission Line	*TL*		*TL* *35 kV*	*Has free dimension*
Circuit-breaker	*Q*		*Q* *VV-10*	*Dimension of rectangle is 10x8 mm*
Disconnectors	*QS*		*QS* *DC-10*	*Dimension of contact line is 10 mm*
AC Cable	–		*Al-10, 0.8 kV, 3 cables*	*Shown as solid line, with graphical showing of cables number*
Measuring Current Transformer	*TA*		*TA* *TA-08*	*Circle has Ø8 mm*
Measuring Voltage Transformer	*TV*		*TV* *TH-08*	*Circle has Ø8 mm*
Flexible bus	–		*Bus*	*Showed as line*
Solid bus	–		*Bus*	*Thickness of bus is 5 mm Connection place made by circle*
Connection point	–		–	*In place where need to show electrical connection it is shown as dot with diameter Ø3 mm*

International Paper Sizes A0, A1, A2, A3, A4. The international paper size standard is ISO 216. It is based on the German DIN 476 standard for paper sizes. ISO paper sizes are all based on a single aspect ratio of the square root of 2, or approximately 1:1.41421. International paper size standards govern the size of sheets of paper used for writing paper, restaurant menus, stationery, business cards, flyers, posters, brochures, and some printed documents. As shown at Figure 7.1.

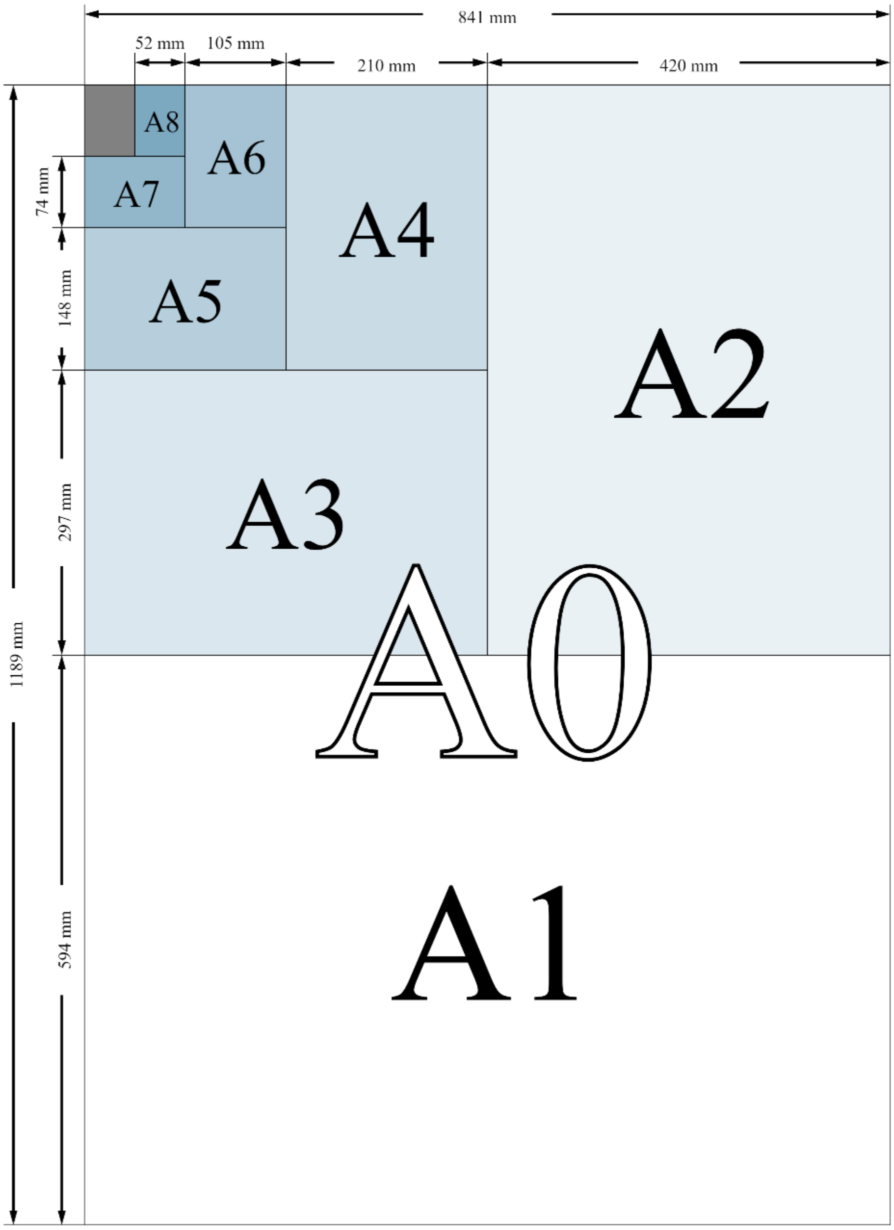


Figure 7.1 – International Paper Sizes

On paper first of all is draw frame with next margins: Top, Right, Bottom – 5 mm, Left – 20 mm (Figure 7.2). and at right-bottom corner draw stamp-table with next dimensions as shown on Figure 7.3.

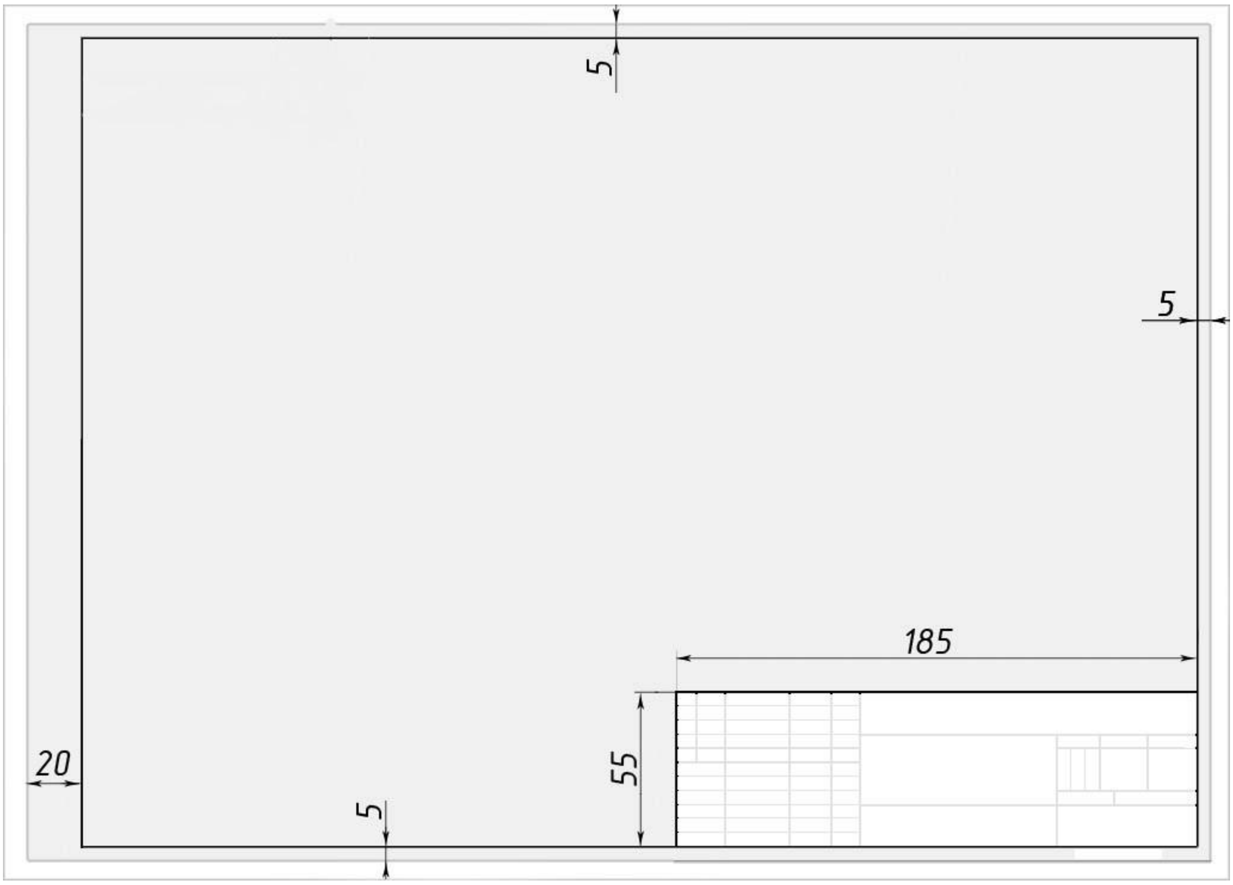


Figure 7.2 – Drawing Margins

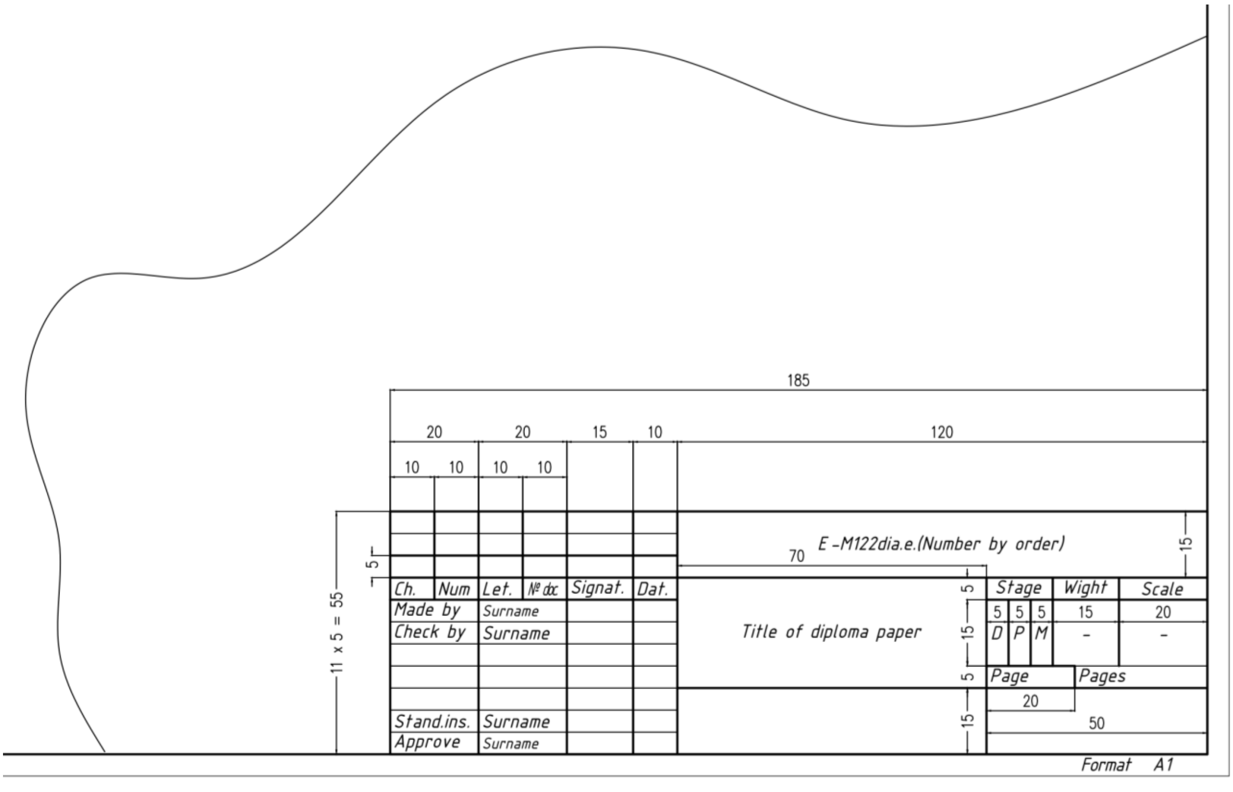


Figure 7.3 – Format stamp-table

Self-testing questions for Drawing part

1) What are the key components included in the DC part of the circuit for a Solar Photovoltaic Power Plant?
2) How should Photovoltaic panels be represented in the schematic diagram?
3) What is the purpose of an Inverter in a Solar Photovoltaic Power Plant, and how should it be depicted in the diagram?
4) How are Combiner boxes and Recombiner boxes represented in the schematic, and what is their function?
5) What type of information should be included next to each element shown in the drawing?
6) What are the recommended text sizes for headers and base text in the Main Electrical Diagram?
7) How should DC Cable Lines be visually represented in the schematic diagram?
8) What is the significance of String fuses and Array fuses in the DC part of the circuit?
9) How are Switch-Disconnectors depicted in the diagram, and what is their role in the system?
10) What components are included in the AC part of the circuit, and how should they be represented in the schematic diagram?

INFORMATION SOURCES

1 Global Solar Atlas [Електронний ресурс] // Solargis. – 2024. – Режим доступу до ресурсу: https://globalsolaratlas.info/map.

2 Honsberg C. PVCDROM [Електронний ресурс] / C. Honsberg, S. Bowden. – 2024. – Режим доступу до ресурсу: https://www.pveducation.org/.

3 Technical Application Paper - Photovoltaic plants. https://new.abb.com/low-voltage/industries/solar. URL: https://search.abb.com/library/Download.aspx?DocumentID=9AKK107492A3277&LanguageCode=en&DocumentPartId=&Action=Launch.

4 Technical Application Papers No.8 - Power factor correction and harmonic filtering in electrical plants. http://www.abb.com/. URL: https://search.abb.com/library/Download.aspx?DocumentID=1SDC007107G0202&LanguageCode=en&DocumentPartId=&Action=Launch.

5 Technical Application Papers No.11 - CEI EN 61439 Part 1 and Part 2. http://www.abb.com/. URL: https://search.abb.com/library/Download.aspx?DocumentID=1SDC007110G0203&LanguageCode=en&DocumentPartId=&Action=Launch.

6 Technical Application Papers No.14 Faults in LVDC microgrids with front-end converters. http://www.abb.com/. URL: https://search.abb.com/library/Download.aspx?DocumentID=1SDC007113G0201&LanguageCode=en&DocumentPartId=&Action=Launch.

7 Technical Application Papers No.2 - MV/LV transformer substations: theory and examples of short-circuit calculation. http://www.abb.com/. URL: https://search.abb.com/library/Download.aspx?DocumentID=1SDC007101G0202&LanguageCode=en&DocumentPartId=&Action=Launch.

8 Technical guide / The MV/LV transformer substations (passive users). http://www.abb.com/. URL: https://search.abb.com/library/Download.aspx?DocumentID=1VCP000591%202015.11&LanguageCode=en&DocumentPartId=&Action=Launch.

9 Technical guide / Smart grids. http://www.abb.com/. URL: https://search.abb.com/library/Download.aspx?DocumentID=1VCP000593%202015.10&LanguageCode=en&DocumentPartId=&Action=Launch.

10 Technical guide - Smart grid - Smart Secondary Substation. http://www.abb.com/. URL:

https://search.abb.com/library/Download.aspx?DocumentID=1VCP000620&LanguageCode=en&DocumentPartId=&Action=Launch.

11 Technical guide / Smart grids - The standard 61850. http://www.abb.com/. URL: https://search.abb.com/library/Download.aspx?DocumentID=1VCP000645&LanguageCode=en&DocumentPartId=&Action=Launch.

12 Installation and operating principles for medium voltage switchgear. http://www.abb.com/. URL: https://search.abb.com/library/Download.aspx?DocumentID=1VCP000630&LanguageCode=en&DocumentPartId=&Action=Launch.

13 Technical guide - Medium voltage DC application. http://www.abb.com/. URL: https://search.abb.com/library/Download.aspx?DocumentID=1VCP000681&LanguageCode=en&DocumentPartId=&Action=Launch.

14 Technical guide - Medium voltage apparatus: technologies and applications. http://www.abb.com/. URL: https://search.abb.com/library/Download.aspx?DocumentID=1VCP000735%20-%202018.05&LanguageCode=en&DocumentPartId=&Action=Launch.

15 TIP: Planung der elektrischen Energieverteilung Technische Grundlagen, Siemens AG Energy Management, Medium Voltage & Systems, Artikel-Nr.: EMMS-T10007-00

16 Nikkhajoei H., Naghaviha D., Karimi H. Step-By-Step Design of Large-Scale Photovoltaic Power Plants. Wiley & Sons, Incorporated, John, 2022.

17 SAM Photovoltaic Model Technical Reference 2016 Update / P. Gilman et al. Office of Scientific and Technical Information (OSTI), 2018. URL: https://doi.org/10.2172/1429291

18 Dunlop, E., Gracia Amillo, A., Salis, E., Sample, T. and Taylor, N., Transitional methods for PV modules, inverters and systems in an Ecodesign Framework, EUR 29513 EN, Publications Office of the European Union, Luxembourg, 2019, ISBN 978-92-79-98284-2, doi:10.2760/496002, JRC114099.

19 Home | Fimer Spa. Home | Fimer Spa. URL: https://www.fimer.com/.

20 Silfab Solar - North American-Made Solar Panels. Silfab Solar - America's Trusted Manufacturer. URL: https://silfabsolar.com/.

21 Transformer Manufacturer | Prolec. Prolec Energy. URL: https://www.prolec.energy/.

22 Solar Brochures ǀ Polycab India Limited. Polycab India Limited. URL: https://polycab.com/product-brochures/solar-brochure.

23 Manufacture & International supply of Electric Cables | Top Cable. Top Cable. URL: https://www.topcable.com/.

24 IEC 60364-5-548:1996. Home page | IEC. URL: https://webstore.iec.ch/en/publication/15782.

25 IEC 60044-8:2002. Home page | IEC. URL: https://webstore.iec.ch/en/publication/157.

26 IEC TR 60909-1:2002. Home page | IEC. URL: https://webstore.iec.ch/en/publication/3888.

27 X. Pei and Y. Kang, "Short-Circuit Fault Protection Strategy for High-Power Three-Phase Three-Wire Inverter," in IEEE Transactions on Industrial Informatics, vol. 8, no. 3, pp. 545-553, Aug. 2012, doi: 10.1109/TII.2012.2187913.

28 Kasikci I. Short Circuits in Power Systems: A Practical Guide to IEC 60909. Wiley & Sons, Incorporated, John, 2020. 278 p.

29 W. Knies, K. Schierack: Elektrische Anlagentechnik, Kraftwerke, Netze, Schaltanlagen, Schutzeinrichtungen, 5th edn, Hanser Verlag, 2000, ISBN-103-446-40574-7.

30 G. Seib: Eelctrical Installations Handbook, 3rd edn, John Wiley & Sons, 2000, ISBN 0-471-49435-6

31 Shah, A. (ed.) (2020). Solar Cells and Modules. Springer International Publishing.

32 J. Duncan Glover, M.S. Sarma, T.J. Overbye, Power System Analysis & Designs, 5th ed., Thomson Learning, Stamford, USA, 2011

33 Verma, A. and Singhal, S. (2015). Solar PV performance parameter and recommendation for optimization of performance in large scale grid connected solar PV plant—case study. Journal of Energy Power Sources 2 (1): 40–53.

34 Switching, Protection and Distribution in Low-Voltage Networks: Handbook with Selection Criteria and Planning Guidelines for Switchgear, Switchboards, and Distribution Systems, Siemens, Germany, Publicis, 1994, ISBN-13: 978-3895780004, Publicis; 2nd revised edition.

35 S.P. Pokharel, S.M. Brahma, S.J. Ranade, Modeling and simulation of three phase inverter for fault study of microgrids, in: North American Power Symposium (NAPS), 2012.

36 Simpson, L.J., Muller, M., Deceglie, M. et al. (2017). NREL efforts to address soiling on PV modules. In: 2017 IEEE 44th Photovoltaic Specialist Conference (PVSC), 2789–2793. IEEE.

37 Louwen, A., de Waal, A.C., Schropp, R.E. et al. (2017). Comprehensive characterisation and analysis of PV module performance under real operating conditions. Progress in Photovoltaics: Research and Applications 25 (3): 218–232.

38 Santiago, I., Trillo-Montero, D., Moreno-Garcia, I.M. et al. (2018). Modeling of photovoltaic cell temperature losses: a review and apractice case in South Spain. Renewable and Sustainable Energy Reviews 90: 70–89.

39 Makrides, G., Zinsser, B., Phinikarides, A. et al. (2012). Temperature and thermal annealing effects on different photovoltaic technologies. Renewable Energy 43: 407–417.

40 Lappalainen, K. and Valkealahti, S. (2017). Effects of PV array layout, electrical conϐiguration and geographic orientation on mismatch losses caused by moving clouds. Solar Energy 144: 548–555.

41 Woyte, A. and Goy, S. (2017). Large grid-connected photovoltaic power plants: best practices for the design and operation of large photovoltaic power plants. In: The Performance of Photovoltaic (PV) Systems, 321–337. Woodhead Publishing.

42 Gasparin, F.P., Bühler, A.J., Rampinelli, G.A., and Krenzinger, A. (2016). Statistical analysis of I–V curve parameters from photovoltaic modules. Solar Energy 131: 30–38.

43 M. Couvreur, E. De Jaeger, A. Robert, 2000, “Voltage Fluctuations and the Concept of Short-Circuit Power”, CIGRE 2000, report 13/14/36-08

44 SIEMENS Power Academy, "Principles of Line Differential Protection," Madrid, 2014.

45 Schneider Electric, Easergy Micom P54x Technical Manual.: Schneider, 2016.

APPENDIX A
EXAMPLE OF CALCULATION DIPLOMA PAPER

At Appendix A shown fully calculated example according to this guide.

A.1 TASK FOR DIPLOMA PAPER AND LITERATURE REVIEW

As an example, will take next **task points**:

- Rated power of PV plant equal to 400 *kW*;
- Location of PV plant is Northwest region of China (select Qinghai 37.422814°, 095.844724°);
- Grid connection at region select voltage level 35 *kV*.

After getting task it needs to make small research of Literature review in which student provide short research about Diploma Paper topic. First of all, good to find out situations of Solar Energy at present country by task and progressive technologies in it. Then, to understand how to provide decisions at part of "Configuration of Photovoltaic Power Plant" for DC and AC part, especially how to place all main equipment (PV panel(s), invertor(s), transformer(s) etc.), it need to understand location area parameters. When you know base information about your topic, you can go to detail calculations. At example not shown citation links on references. You must do not forgotten put citation links during your calculations on references which you use in view: [1]. Which is mean that in this very place you use reference number one from list.

Structure of calculations:

Title page
Abstract
Contents
Abbreviations
Introduction
1 Literature review
2 Calculations of Power according to Insolation's
3 Configuration of Photovoltaic Power Plant of DC side
4 Equipment selection of DC part
5 Configuration of Solar Photovoltaic Power Plant on AC side
6 Selecting of main commutation equipment of AC side
Conclusions
References

Drawing Main electrical scheme (Dodatok)

A.2 CALCULATIONS OF POWER ACCORDING TO INSOLATION'S

For making calculations is recommended to use Global Solar Atlas web resource.

A.2.1 Interactive maps of Global Solar Atlas

According to task we aimed to explore solar parameters of designed Photovoltaic Power Plant at China, in the Northwest region, Qinghai (37.422814°, 095.844724°).

On Figure A.2.1 showed Photovoltaic Power Potential of China, from which we can see that Northwest region have huge solar potential which allowed design 400 MW Photovoltaic Power Plant.

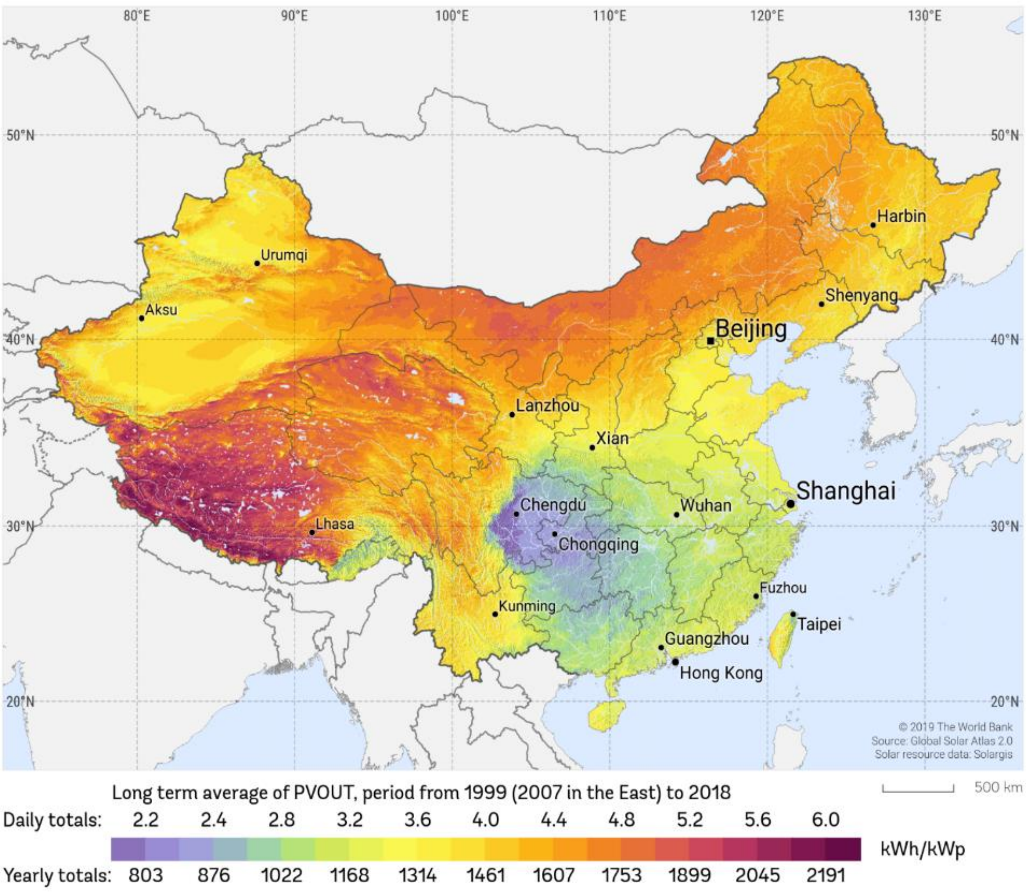


Figure A.2.1 – Photovoltaic Power Potential of China

As next step, at Figure A.2.2 showed PVOUT according to coordinates of task, where we can see potential of chosen region, and on Figure A.2.3 showed satellite map of coordinates. Figure A.2.4 showed data of horizon and sunpath at point.

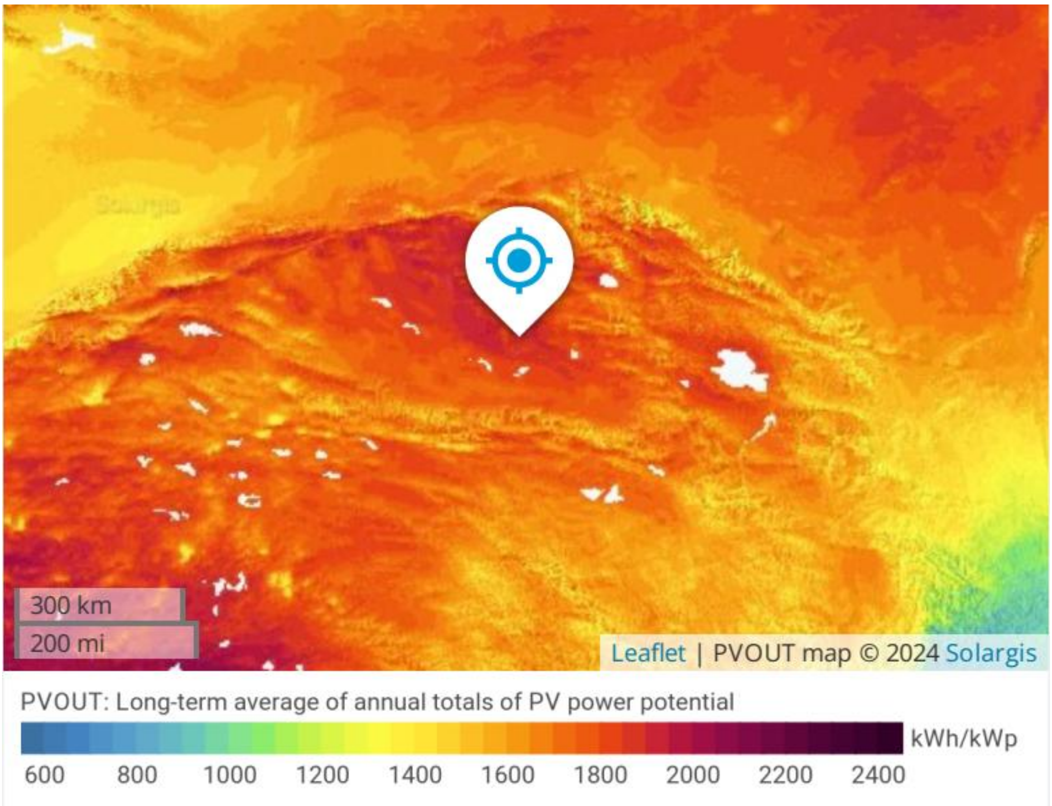


Figure A.2.2 – PVOUT map of coordinates

Figure A.2.3 – Satellite map

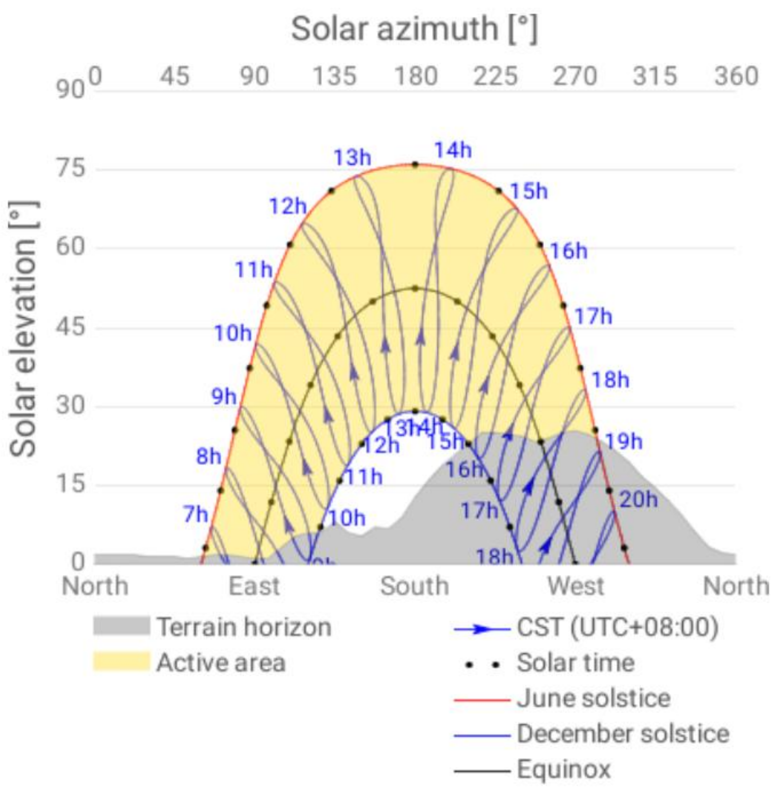


Figure A.2.4 – Horizon and sunpath

Table A.2.1 shows map data parameters per year of chosen region. Air temperature at table is temperature at day when we collect data.

Table A.2.1 – Map Data per year

Parameter	Abbreviation	Value
Direct normal irradiation	DNI	1892.4 kWh/m^2
Global horizontal irradiation	GHI	1810.6 kWh/m^2
Diffuse horizontal irradiation	DIF	649.4 kWh/m^2
Global tilted irradiation at optimum angle	GTI_{opta}	2161.5 kWh/m^2
Optimum tilt of PV modules	OPTA	38 / 180 °
Air temperature	TEMP	2.9 $°C$
Terrain elevation	ELE	3290 m

A.2.2 Photovoltaic energy yield calculations

By using PV yield calculator of Global Solar Atlas, it allows us calculate long-term energy yield for defined according to the task PV system. We chose large scale ground-mounted PV plant, as shown at Figure A.2.5.

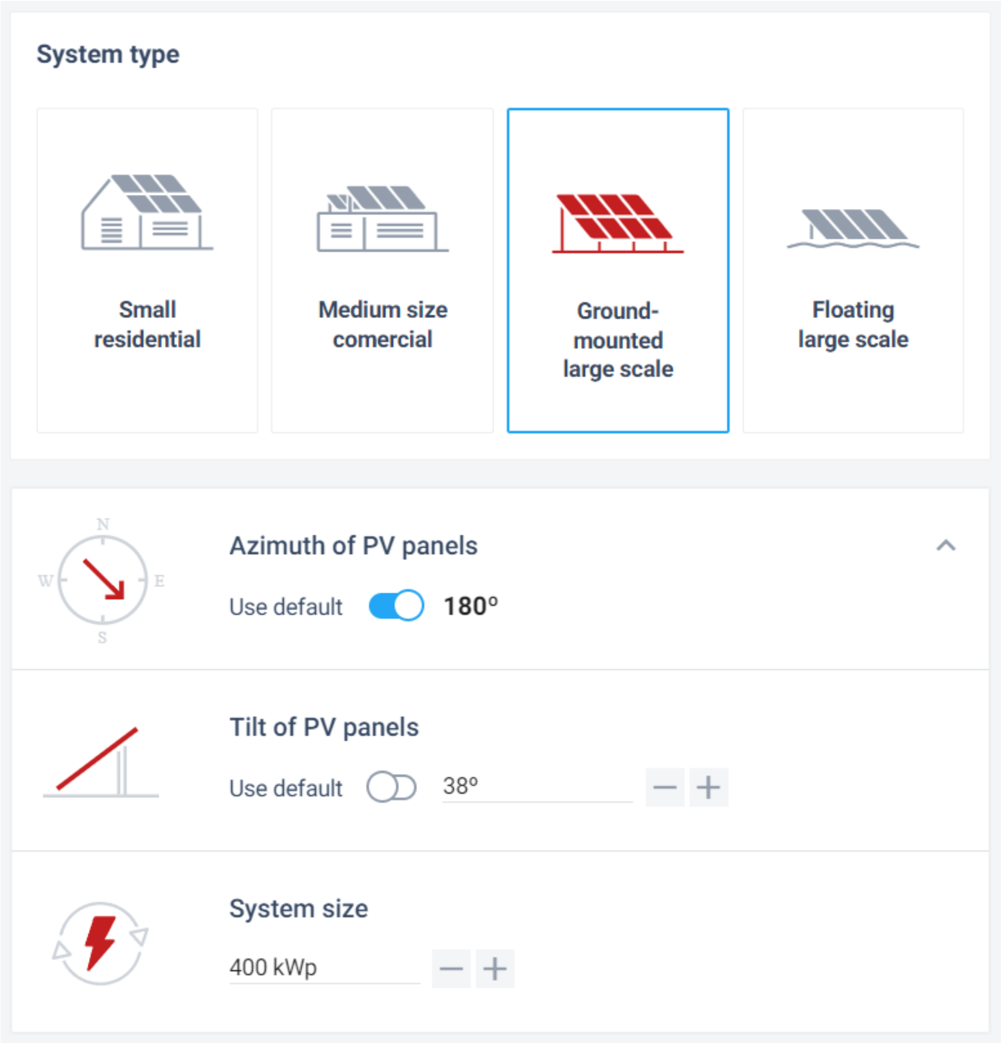


Figure A.2.5 – Configurations of system type [15]

A.2.2.1 PV electricity

Those system configurations give to us, by Global Solar Atlas, give total photovoltaic power output 700.614 *MWh per year*, and Global tilted irradiation 2115.6 *kWh/m*^{2} *per year*. Calculator give us possibility to detailed discover this data, at Figure A.2.6 showed monthly averages, Figure A.2.7 and Figure A.2.8 showed average hourly profiles as profiles and as detailed data of total photovoltaic power output.

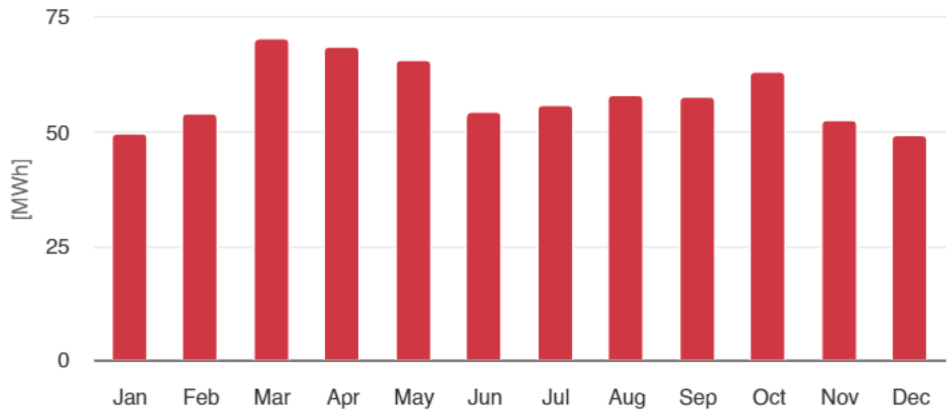


Figure A.2.6 – Monthly averages, *MWh*, Total photovoltaic power output

Figure A.2.7 – Average hourly profiles, *kWh*, Total photovoltaic power output

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0 - 1												
1 - 2												
2 - 3												
3 - 4												
4 - 5					0.910	1.749	0.337					
5 - 6			0.180	5.540	15.688	17.948	13.042	6.001	1.989	0.074		
6 - 7		0.795	24.962	51.080	58.841	51.648	45.147	42.455	42.713	37.769	1.812	
7 - 8	29.549	73.015	103.572	123.864	127.005	105.575	100.234	100.655	112.362	132.759	105.934	38.314
8 - 9	153.790	160.880	185.033	203.943	193.935	160.367	156.773	162.565	181.468	212.863	208.141	181.129
9 - 10	230.404	241.813	270.717	271.464	245.988	203.668	204.017	217.967	238.713	277.506	277.603	265.582
10 - 11	282.979	299.131	315.000	308.771	272.435	226.707	229.797	249.647	266.399	310.198	312.035	309.139
11 - 12	300.543	313.899	328.715	320.214	285.114	234.223	240.201	255.244	270.583	313.613	317.985	318.731
12 - 13	302.634	319.655	327.954	314.511	275.180	230.572	231.084	249.393	261.365	299.596	300.804	306.980
13 - 14	271.213	305.536	307.270	284.840	248.479	213.288	211.596	228.811	239.322	265.317	201.392	148.185
14 - 15	18.205	199.759	258.222	226.624	197.170	172.773	171.038	187.700	188.352	164.679	16.469	14.302
15 - 16	12.223	17.706	137.708	149.399	133.577	119.259	120.691	127.348	102.378	19.613	9.781	7.058
16 - 17	1.390	6.899	15.481	21.539	52.695	59.178	60.688	41.776	18.111	3.356	0.551	0.160
17 - 18			1.854	6.303	13.744	19.883	18.953	10.498	1.582			
18 - 19					0.761	3.469	2.114	0.121				
19 - 20												
20 - 21												
21 - 22												
22 - 23												
23 - 24												
Sum	1,603	1,939	2,277	2,288	2,122	1,820	1,806	1,880	1,925	2,037	1,753	1,590

Figure A.2.8 – Detailed average hourly profiles, *kWh*, Total photovoltaic power output

A.2.2.2 Solar radiations

System configuration by solar radiation give direct normal irradiation in annual averages – 1863.1 *kWh/m*^{2} *per year*. Detailed discover this number. Figure A.2.9 showed monthly averages, Figure A.2.10 and Figure A.2.11 showed average hourly profiles as profiles and as detailed data of direct normal irradiation.

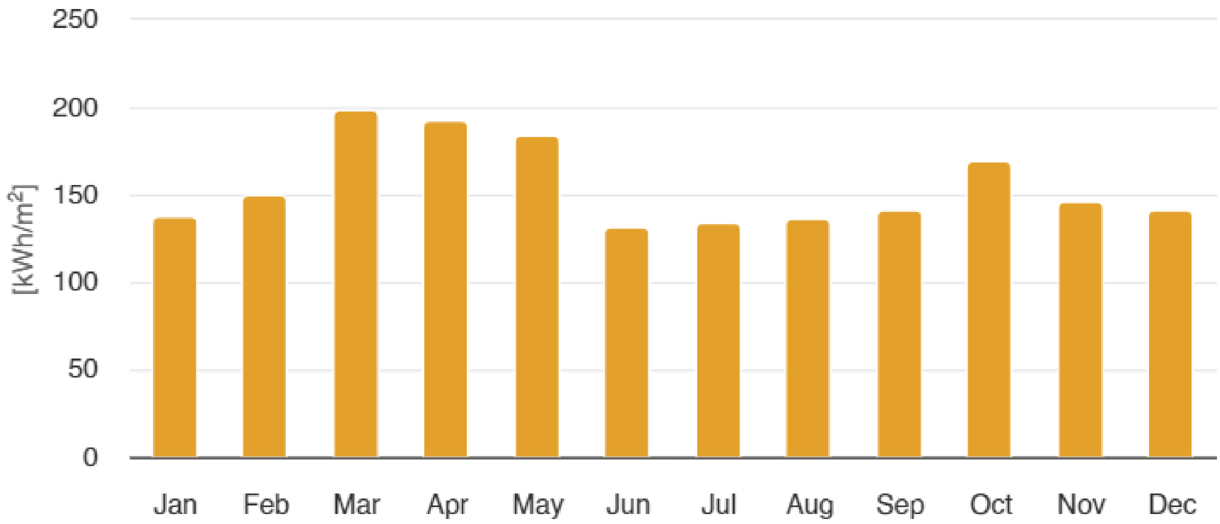


Figure A.2.9 – Monthly averages, *kWh/m*^{2}, Direct normal irradiation [15]

Figure A.2.10 – Average hourly profiles, *Wh/m²*, Direct normal irradiation [15]

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0 - 1												
1 - 2												
2 - 3												
3 - 4												
4 - 5					8	17						
5 - 6				72	198	149	105	46	18			
6 - 7			181	358	366	257	241	229	228	202		
7 - 8	182	338	436	473	470	343	335	331	381	491	457	228
8 - 9	539	522	560	607	557	410	407	417	479	621	657	627
9 - 10	657	670	729	710	609	442	451	483	553	719	774	778
10 - 11	745	774	795	744	619	449	463	511	569	754	817	838
11 - 12	780	795	818	755	633	449	467	504	563	747	822	845
12 - 13	798	828	822	756	623	448	454	495	556	735	796	832
13 - 14	751	830	811	733	613	447	441	487	549	712	558	399
14 - 15		583	784	668	556	416	403	453	494	483		
15 - 16			472	555	482	354	345	380	309			
16 - 17					207	210	205	80				
17 - 18												
18 - 19												
19 - 20												
20 - 21												
21 - 22												
22 - 23												
23 - 24												
Sum	4,453	5,338	6,407	6,430	5,942	4,391	4,316	4,413	4,699	5,463	4,878	4,545

Figure A.2.11 – Detailed average hourly profiles, *Wh/m²*, Direct normal irradiation

A.2.3 Temperature

For future calculations, our next step is finding out maximum and minimum temperature data. For this purpose, we use NASA web recourse to get data of whole year to find needed temperature information's. This data shows at Figure A.2.12 as graphic.

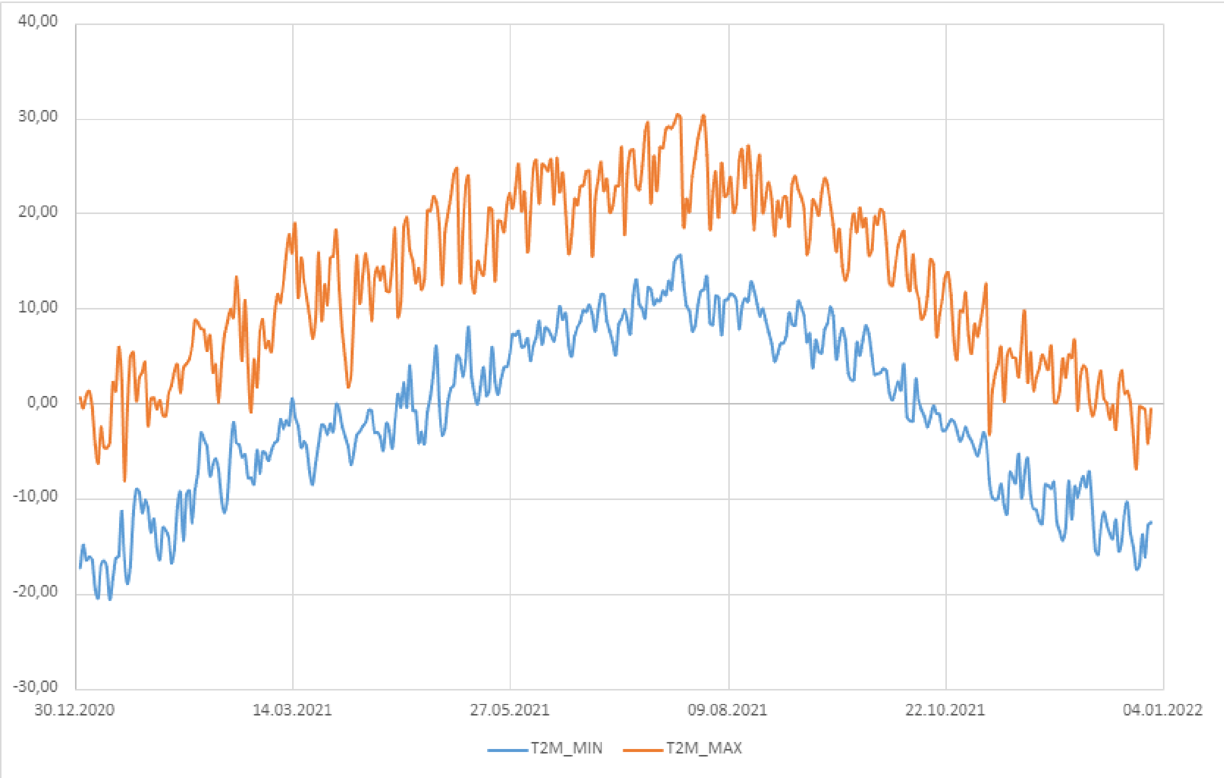


Figure A.2.12 – Maximum and minimum temperature data from NASA at Qinghai (37.422814°, 095.844724°) [16]

A.3 CONFIGURATION OF PHOTOVOLTAIC POWER PLANT OF DC SIDE

A.3.1 Inverter size and PV module selection

A.3.1.1 PV module selection

Project sized into initial data as 400 kW, for this we consider PV panels of Silfab SOLAR firm, series SIL400 (Figure A.3.1). Technical data of this panels given at Table A.3.1 and Table A.3.2.

Table A.3.1 – Silfab SOLAR series SIL 400 W

Parameter \ Type		SIL- 400
Electrical specifications		
Module Power (P_{max})	*Wp*	400
Maximum power voltage (V_{pmax})	*V*	36.05
Maximum power current (I_{pmax})	*A*	11.10
Open circuit voltage (V_{oc})	*V*	43.02
Short circuit current (I_{sc})	*A*	11.58
Module efficiency	*%*	20.2
Maximum system voltage (V_{DC})	*V*	1000
Series fuse rating	*A*	20
Power Tolerance	*Wp*	0/+10
Temperature ratings		
Temperature Coefficient I_{sc}	*%/C*	0.064
Temperature Coefficient V_{oc}	*%/C*	-0.28
Temperature Coefficient P_{max}	*%/C*	-0.36
NOCT (± 2°*C*)	*°C*	16,8
Operating temperature	*°C*	-40/+85
Mechanical properties / Components		
Module weight	*kg*	21.3
Dimensions (*H / L / D*)	*mm*	1914/1036/35

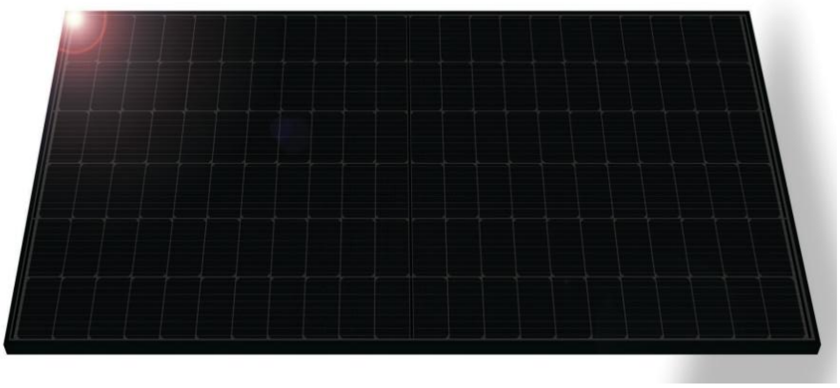


Figure A.3.1 – Silfab SOLAR series SIL400

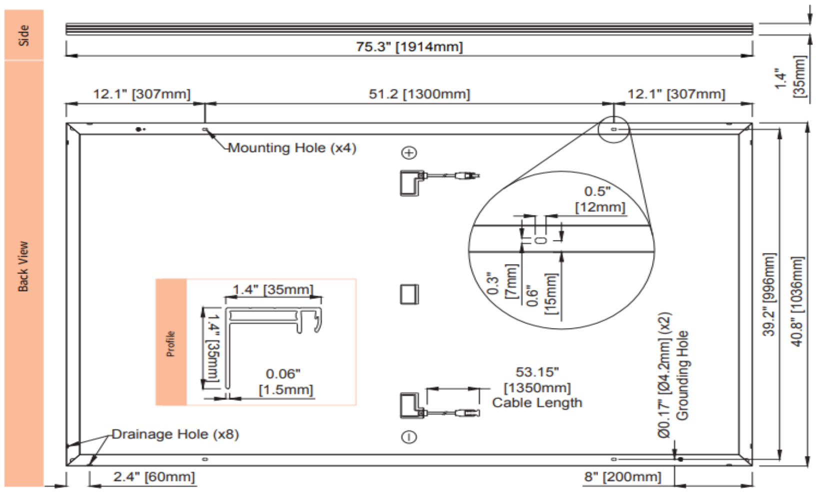


Figure A.3.2 – Dimensions parameters of Silfab SOLAR series SIL400

A.3.1.2 Inverter selection

Inverter and its sizing ($P_{DC\ Max\ Inverter}$) must be select in accordance to PV modules rated power ($P_{DC\ PV\ GEN}$). Ratio of its selection must be next:

$$P_{DC\ Max\ Inverter} > P_{DC\ PV\ GEN} \qquad (A.3.1)$$

$$2 \cdot 250 > 400$$

From the initial data rated power of PV Power Plant is 400 kW, according to that chose 2 central inverters of ABB firm – PVS800-57-0250kW-A. Technical data of inverter presented at Table A.3.2. Scheme of basic design and power network connection of these two inverters shown at Figure A.3.3.

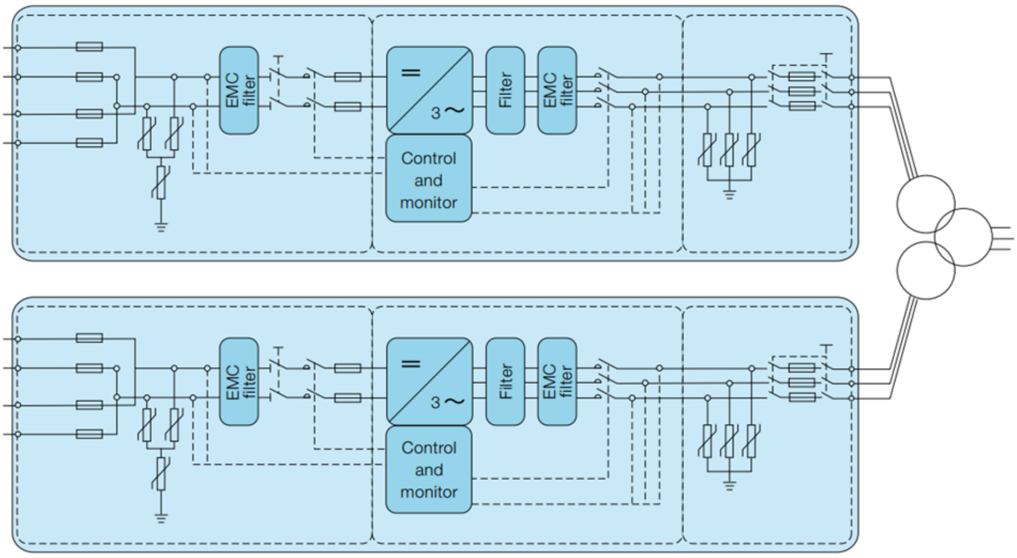


Figure A.3.3 – ABB PVS800 250 kW central inverter design and power network connection

Table A.3.2 – ABB central inverters PVS800 250 kW [18]

Parameter \ Type	PVS800-57-0250kW-A
Input (DC)	
Maximum input power ($P_{PV,\ max}$)	300 *kWp*
DC voltage range, mpp ($U_{DC,\ mpp}$)	450 to 825 *V*
Maximum DC voltage ($U_{max\ (DC)}$)	1000 *V*
Maximum DC current ($I_{max\ (DC)}$)	600 *A*
Number of protected DC inputs	2, 4, 8 *(+/-)*
Output (AC)	
Nominal power ($P_{N(AC)}$)	250 *kW*
Maximum output power	250 *kW*
Power at cosφ = 0.95	240 *kW*
Nominal AC current ($I_{N(AC)}$)	485 *A*
Nominal output voltage ($U_{N(AC)}$)	300 *V*
Output frequency	50/60 *Hz*
Harmonic distortion, current	< 3*%*
Distribution network type	*TN* and *IT*
Efficiency	
Maximum	98.0 *%*
Euro-eta	97.6 *%*
Power consumption	
Own consumption in operation	310 *W*
Standby operation consumption	60 *W*
Environmental limits	
Ambient temp. range (nom. ratings)	-15 to +40 *°C*
Degree of protection	IP 42
Dimensions and weight	
Width/Height/Depth, mm	1830/2130/680
Protection	
Ground fault monitoring	YES
Grid monitoring	YES
Anti-islanding	YES
DC reverse polarity	YES
AC and DC short circuit and over current	YES
AC and DC over voltage and temperature	YES

A.3.2 Determining the PV module max V_{oc}

Determination of V_{oc} provided with using technical data from Table A.3.2.

The maximum open circuit voltage $V_{oc\ MAX}$ can be calculated using the following data:

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

- PV module temperature coefficient.

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

$$V_{OC\ MAX} = V_{OC\ STC}\left[1 + \frac{\beta}{100}\cdot\left(T_{\min} - 25\right)\right] \tag{A.3.2}$$

where $T_{\min}$ – assumed equal to the lowest temperature that can be expected at the PV installation location, °C;

$V_{OC\ STC}$ – the PV module open circuit voltage at standard test conditions, V;

β – the variation coefficient of the voltage according to temperature and depends on the typology of PV module; it is measured in, *%/°C*.

$$V_{OC\ MAX} = 43.2\left[1 + \frac{-0.28}{100}\cdot\left(-20.6 - 25\right)\right] = 48.71$$

A.3.3 Determining the PV module min V_{MPP}

On the basis of the above, the minimum MPP voltage V_{MPP} min can be calculated using the following data:

- maximum temperature that can be expected at the PV installation location;
- PV module MPP voltage at STC condition VMPP STC;
- PV module temperature coefficient.

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

The formulas to calculate $V_{MPP\,\min}$, V, are:

$$V_{MPP\ \min} = V_{MPP\ STC}\left[1 + \frac{\beta}{100}\cdot\left(T_{cell} - 25\right)\right] \tag{A.3.3}$$

where T_{cell} – the maximum cell temperature that can be expected at the PV installation location, *°C* or *K*;

$V_{MPP\ STC}$ – the PV module MPP voltage at standard test conditions, *V*.

$$V_{MPP\,\min} = 36.05\left[1 + \frac{-0.28}{100}\cdot\left(30.3 - 25\right)\right] = 35.5$$

A.3.4 Determining the Maximum Number of PV Modules per String

The maximum number of PV modules connected in series that could be connected to the inverter is defined based on paragraph Determining the PV module max V_{oc} and Table A.3.1 – A.3.2. The maximum number $N_{MAX\ Module}$ of PV modules must be round down, calculated as:

$$N_{MAX\ Module} \le \frac{V_{MAX\ Inverter}}{V_{OC\ MAX\ Module}} \qquad (A.3.4)$$

where $V_{MAX\ Inverter}$ – the maximum input voltage of inverter, V;

$V_{OC\ MAX\ Module}$ – the PV module maximum V_{oc}, V.

$$N_{MAX\ Module} \le \frac{1000}{48.7} \approx 20$$

A.3.5 Determining the PV string max V_{oc}

The maximum open circuit voltage of the string ($V_{OC\ MAX\ String}$) calculated as follow, V:

$$V_{OC\ MAX\ String} = N_{MAX\ Module}\cdot V_{OC\ MAX\ Module} \qquad (A.3.5)$$

$$V_{OC\ MAX\ String} = 20\cdot 48.7 = 974$$

A.3.6 Determining the Minimum Number of PV Modules per String

The minimum number of PV modules $N_{\min\ Module}$ connected in series connected to the inverter is defined based on the assumption that the string voltage at MPP condition is always above the minimum MPP voltage of the inverter, based on paragraph Determining the PV module min V_{MPP} and Table A.3.2, must be round up, calculate as:

$$N_{\min\ Module} \geq \frac{V_{\min\ MPPT\ Inverter}}{V_{MPP\ \min\ Module}} \qquad (A.3.6)$$

where $V_{\min\ MPPT\ Inverter}$ – the minimum MPP voltage of the inverter, *V*.

$$N_{\min\ Module} \geq \frac{450}{35.5} \approx 13$$

A.3.7 Number of PV Modules per String

The number of PV modules per string $\left(N_{Module}\right)$ determine based on paragraphs Determining the Maximum Number of PV Modules per String and Determining the Minimum Number of PV Modules per String according to ratio:

$$N_{Min\ Module} \leq N_{Module} \leq N_{Max\ Module} \qquad (A.3.7)$$

$$13 \leq N_{Module} \leq 20$$

A.3.8 Determining the Maximum PV Module Current

The maximum PV module short-circuit current $I_{sc\ MAX\ Module}$ calculated by using the following data:

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

The temperatures of the solar cells depend on the selected mounting system and on the ambient temperature, and based on Table A.3.1. The formulas to calculate $I_{SC\ MAX}$, *A*, are:

$$I_{SC\ MAX\ Module} = I_{SC\ STC}\left[1 - \frac{\alpha}{100}\cdot\left(25 - T_{cell}\right)\right] \qquad (A.3.8)$$

where $I_{SC\ STC}$ – the PV module short-circuit current at standard test conditions, *A*;

α – the variation coefficient of the current according to temperature and depends on the typology of PV module; it is measured in, *%/°C* or *%/K*.

$$I_{SC\ MAX\ Module} = 11.58\left[1 - \frac{0.064}{100}\cdot(25 - 30.3)\right] = 11.6$$

A.3.9 Determining the Maximum PV string Current

The total current in a string of PV modules connected in series is equal to the current generated by the single module, the maximum string short-circuit current $I_{sc\ MAX\ string}$ is equal to the maximum PV module short-circuit current $I_{sc\ MAX\ module}$, A:

$$I_{SC\ MAX\ Module} = I_{SC\ MAX\ String} \tag{A.3.9}$$

$$I_{SC\ MAX\ String} = 11.6$$

A.3.10 Determining the String Number

The maximum number of strings connected in parallel that could be connected to the single DC input channel of the inverter is defined based on the assumption that the maximum string short-circuit current $I_{sc\ MAX\ string}$ is always below the maximum input current of the single DC input channel of the inverter. Must be round down, calculate as:

$$N_{MAX\ String} \le \frac{I_{MAX\ input}}{I_{SC\ MAX\ String}} \tag{A.3.10}$$

$$N_{MAX\ String} \le \frac{600}{11.6} \approx 51$$

A.3.11 Array physical configuration

During the design phase, the self-shading effects shall be considered in the ground-mounted PV system with fix free standing PV arrays. The self-shading losses are caused by a preceding row of PV modules and it applies to all but the first row of PV modules. With a careful planning the self-shading losses can be reduced to a minimum. PV designer use different assumptions to define the minimal distance d between neighboring rows. As shown at Figure A.3.4.

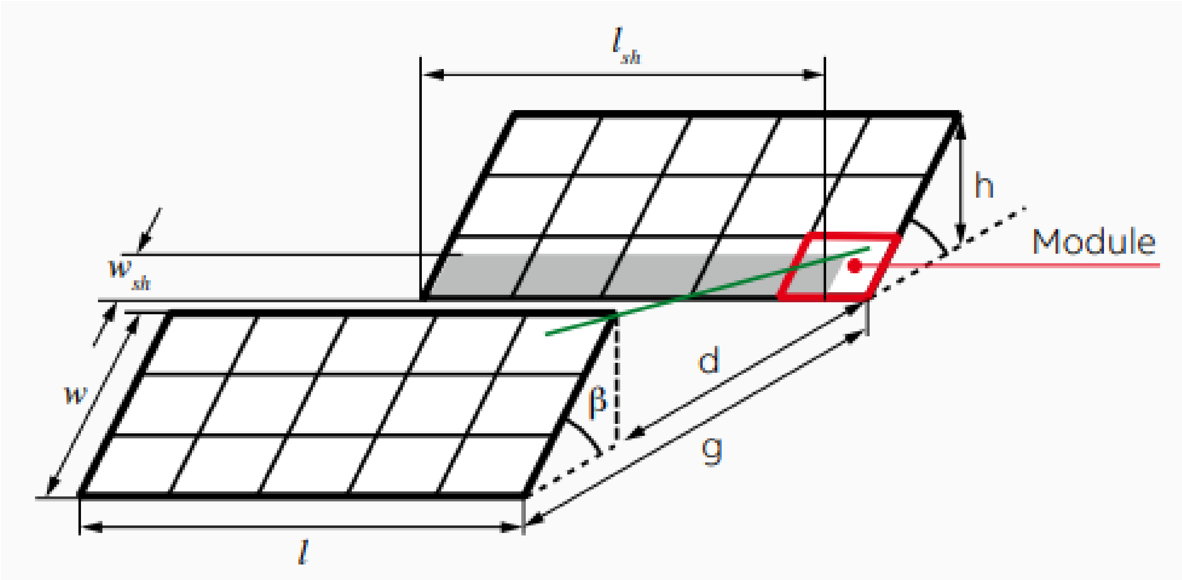


Figure A.3.4 – Distance between neighboring rows – row spacing

In our case the panel tilted 38° is composed by 3 modules in landscape condition, as shown on Figure A.3.5.

Figure A.3.5 – Design panel of PV module in landscape conditions

The width *w* of the panel, *mm*, is:

$$w = n \cdot h_{module} \tag{A.3.11}$$

where n – number of modules;

h_{module} – width of the module, *mm*.

$$w = 3 \cdot 1036 = 3108$$

Height difference (h) from the back of the module to the surface, calculates, *mm*, as:

$$h = w \cdot \sin\beta \qquad \text{(A.3.12)}$$

where β – installation tilt of panels, °.

$$h = 3108 \cdot \sin 38^\circ = 1913$$

The panels row spacing (d) calculate, *mm*, as:

$$d = \frac{h}{\tan\theta} \qquad \text{(A.3.13)}$$

where θ – the sun elevation, °.

As shown on Figure A.2.4, at 10:00 AM, in the place of the PV installation, the sun elevation (θ) is around 14°. At 2:00 PM, in the place of the PV installation, the sun elevation (θ) is around 27°. The minimum elevation is 14°.

$$d = \frac{1913}{\tan 14^\circ} = 7674$$

The row width calculates as:

$$g = d + w \cdot \cos\beta \qquad \text{(A.3.14)}$$

$$g = 7674 + 3108 \cdot \cos 38^\circ = 10123$$

A.3.12 Definitive inverter layout

At the beginning of chapter, we decide to use 2 central invertors with rated capacity of 250 kW. For each invertor from PV field income 200 *kWp*.

First of all, we need to define total number of PV panels $\left(N_{module\ PV\ plant}\right)$, as:

$$N_{module\ PV\ plant} = \frac{P_{DC\ PV\ GEN}}{P_{module}} \qquad \text{(A.3.15)}$$

where P_{module} – active power of one PV panel, Table A.2.1, *kWp*.

$$N_{module\ PV\ plant} = \frac{400 \cdot 10^3}{400} = 1000$$

According to paragraph A.3.7we need to define number of strings connected to inverter $\left(N_{\min strings\, inverter}\right)$, which is calculate as:

$$N_{\min strings\, inverter} = \frac{N_{module\ PV\ plant}}{N_{MAX\ module} \cdot N_{inverters}} \qquad \text{(A.3.16)}$$

where $N_{inverters}$ – number of inverters;

$$N_{\min strings\, inverter} = \frac{1000}{20 \cdot 2} = 25$$

To design inverter layout, we checked is inverter inputs is enough to connect minimal number of strings or we will need to use combiner boxes. For that we compare number of invertors $\left(N_{inverter\, inputs}\right)$ inputs and minimal number of strings $\left(N_{\min strings\, inverter}\right)$:

$$N_{\min strings\, inverter} \le N_{inverter\, inputs} \qquad \text{(A.3.17)}$$

$$25 \le 8$$

From the ratio we seen that we need to use combiner boxes.

In order to maximize the power connected and linearized of power separation on inputs, the best stringing option is: 5 strings of 20 PV modules connected to each combiner box; 5 combiner boxes connected to each inverter. Structure diagram, connected to Figure A.3.6, where n = 20, m = 5, M = 5. From Table A.3.2, where shown types of combiner boxes, we chose to installing combiner box with 6 inputs.

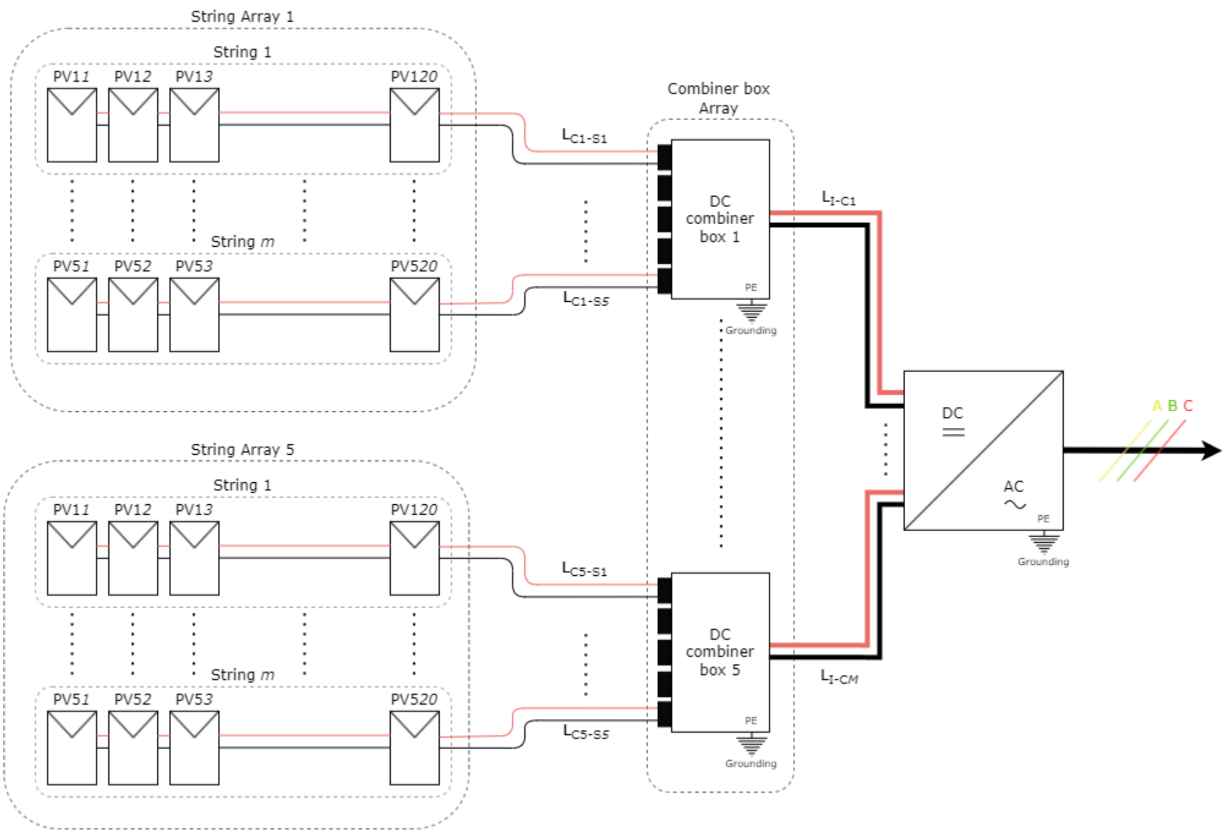


Figure A.3.6 – Single-line diagram of DC side of a one invertor

Table A.3.3 – Technical data for Combiner boxes 1000*V*

Maximum Voltage, *V*	1000											
Number of DC Input (+ & -, optional)	4	6	8	10	12	14	16	18	20	24	28	32
Fuse Max Size, *A*	20											

According to designed layout takes next cables length between parts of layout:

- 25 Cable Lines from Combiner boxes to String – $L_{C\text{-}S}$ = 100 m;
- 5 Cable Lines from Inverter to Combiner boxes – $L_{I\text{-}C}$ = 150 m.

A.4 EQUIPMENT SELECTION OF DC PART

A.4.1 Cables cross-sectional area and current carrying capacity

Main condition of cross-section $\left(S_{cross-section}\right)$ selection based on choosing from nominal values by minimal allowance according to current cross-section of cable $\left(S_{\min}\right)$, mm^2:

$$S_{cross-section} \geq S_{\min} \tag{A.4.1}$$

$$S_{\min} = \frac{\rho \cdot L \cdot I_{section}}{\partial V_{\max}} \tag{A.4.2}$$

where L – length of the conductor of section, *m*;

ρ – specific resistance of the cable material, $\frac{\Omega \cdot mm^2}{m}$: 0.0175 – for copper; 0.0281 – for aluminium;

$I_{section}$ – nominal current rating, *A*;

$\partial V_{\max}$ – maximum allowed voltage drops, *V*.

$$\partial V_{\max String} = \frac{\alpha}{100} \cdot V_{OC\ MAX\ string} \tag{A.4.3}$$

where α – percentage of allowance voltage drop, 3%;

$V_{OC\ MAX\ string}$ – maximum open circuit voltage with voltage multiplication factor, paragraph Determining the PV string max V_{oc}.

A.4.1.1 PV modules string cables

Firstly, calculate according to formulas from paragraph Cables cross-sectional area and current carrying capacity cable for string:

$$\partial V_{\max String} = \frac{3}{100} \cdot 974.39 = 29.23$$

$$S_{\min String} = \frac{0.0281 \cdot 100 \cdot 11.62}{29.23} = 1.12$$

By calculated data take cable cross-section 1.5 and cable “Al 1.5” (Table A.4.1).

Table A.4.1 – Aluminium PV cable 1500 *V*, according to IEC 60502-1

Type	Cross-section, mm^2	The continuous current-carrying capacity I_z	
		Open air current, *A*	On surface current, *A*
Al 1,5	1.5	30	29

To be sure that chosen cable will work reliable, next step is checking cable by the continuous current-carrying capacity I_z of the PV string cables, it must be greater than the short-circuit maximum current of the string, by next ratio:

$$I_z \geq I_{SC\ MAX\ string} \quad (A.4.4)$$

$$30 \geq 11.61$$

The condition is fulfilled.

A.4.1.2 Array cables

By the same algorithm calculate needed parameters with previous voltage drop, and check reliable of cable cross-section.

$$\partial V_{\max Array} = \frac{\alpha}{100} \cdot \left(V_{OC\ MAX\ string} - \partial V_{\max String}\right) \quad (A.4.5)$$

$$\partial V_{\max Array} = \frac{3}{100} \cdot (974.39 - 29.23) = 28.35$$

Array current for cross-section $I_{SC\,MAX\ Array}$, *A*, calculate as:

$$I_{SC\,MAX\ Array} = I_{SC\,MAX\ string} \cdot N_{string} \quad (A.4.6)$$

$$I_{SC\,MAX\ Array} = 11.61 \cdot 5$$

$$S_{\min Array} = \frac{0.0281 \cdot 150 \cdot 58.1}{28.35} = 8.63$$

By calculated data take cable cross-section 10 and cable “Al 10” (Table A.4.2).

Table A.4.2 – Aluminum PV cable 1500 *V*, according to IEC 60502-1

Type	Cross-section, mm^2	The continuous current-carrying capacity I_z	
		Open air current, *A*	On surface current, *A*
Al 10	10	98	93

Reliable checking:

$$I_z \geq I_{SC\ MAX\ array} \quad (A.4.7)$$

$$98 \geq 58.1$$

The condition is fulfilled.

A.4.2 Protecting devices

A.4.2.1 Choosing of string protective devices

Each strings need to protect by Fuse with an overcurrent protection device.

Where the nominal overcurrent protection rating of the string overcurrent protection device shall be I_n where:

$$1.5 \cdot I_{SC} \leq I_n < 2.4 \cdot I_{SC} \quad (A.4.8)$$

where I_{SC} – short-circuit current in Fault point, according to choosing Fuse on string, take into account that $I_{SC} = I_{SC\,MAX\ string}$, *A*.

By I_n nominal parameter of Fuse current selection, for reliability we take Fuse from ratio:

$$I_n \leq I_{rev\ module} \quad (A.4.9)$$

where $I_{rev\ module}$ – the maximum reverse current that the PV modules allow; it is indicated in the PV modules datasheet (Table A.2.1).

$$17.42 \leq I_n < 27.86$$

$$I_n \leq 20$$

Take Fuse with $I_n = 20$ and nominal voltage 1000 *V* (Table A.4.).

Table A.4.3 – Technical data of Fuses 1000 *V*

Model	Rated Current (A)	Rated Voltage (V_{DC})	I^2t (A^2s) Pre-earcing	I^2t (A^2s) Total Power
20A10	20	1000	16.7	372.0

A.4.2.2 Choosing of switching and disconnecting devices

Switching devises is chooses for Array of Strings (for Combiner Box), by voltage and current. When choosing a DC switch, the following parameters are taken into consideration:

- Rated insulation voltage U_i;
- Rated operating voltage U_e;
- Rated operating current I_e.

For this data take Switch-disconnectors SD75, technical data of which shown at Table A.4.4.

Table A.4.4 – Technical data of switch-disconnectors

Name	SD75
Nominal current I_n, A	75
Number of poles	2, 3, 4
Maximum voltage U_e, V	1500
Maximum operating temperature in box without $I_{th} \cdot derating$, °C	40

To check reliability of Switch-disconnectors we check Rated operating current calculate as I_e, A:

$$I_e > \frac{I_{SC\,MAX\ Array}}{k_T} \tag{A.4.10}$$

where $I_{SC\,MAX\ Array}$ – the total short-circuit currents of the array;

k_T – the switch derating factor, determined by Figure A.4.1.

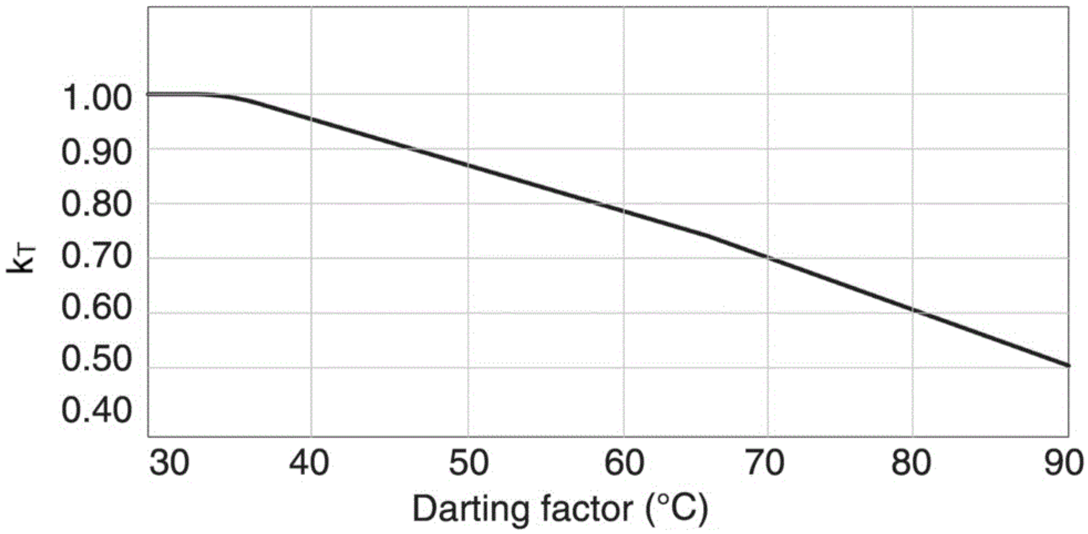


Figure A.4.1 – Determining curve k_T

$$I_e = 75 > \frac{58.1}{0.97} = 59.9$$

The condition is fulfilled.

A.5 CONFIGURATION OF SOLAR PHOTOVOLTAIC POWER PLANT ON AC SIDE

According to DC part calculation and takes decision, at project present 2 invertors which connect DC and AC parts. At AC side invertors thought cables connect to transformer substation and next to Power Grid. At Figure A.5.1 shown its base structure.

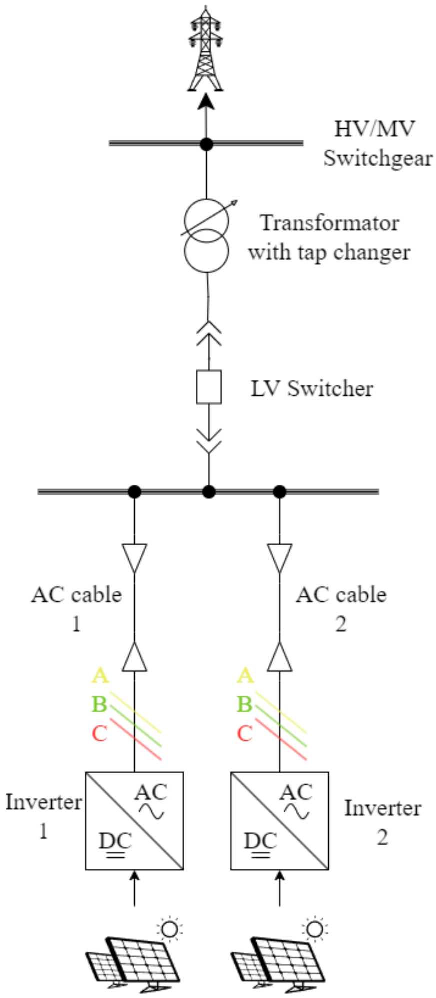


Figure A.5.1 – Base structure of PV Power Plant Grid connection

A.5.1 Transformer substation

A.5.1.1 Transformer substation layout

Rated power of choses invertor is 250 *kW*, a sum is 500 *kW*, this data for *cosφ*=1. In case when we have *cosφ*=1 full power of invertors output is 500 *kVA*. For such power rate, voltage level of high side (35 kV according to initial data) and reliable of PV Power Plant take to design transformer substation with single transformer (Figure A.5.2).

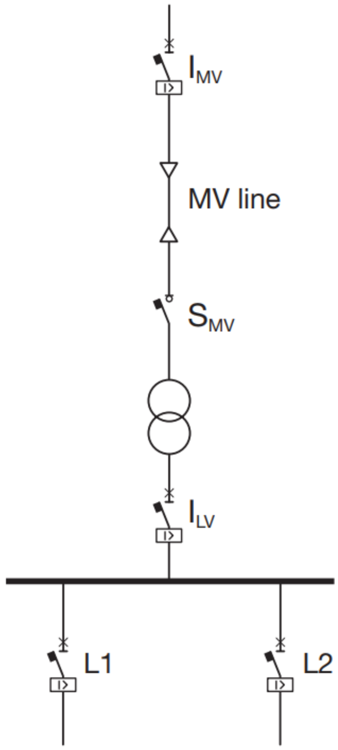


Figure A.5.2 – Substation with single transformer, N_{tr}=1

A.5.1.2 Transformer selection

After transformer substation layout we need to select transformer.

First of all, transformer for PV Power Plant must have special low voltage level, which must response to invertor output voltage level. Then it must have tap changer with small steps, because of unstable power generation by PV panels during the day.

Rated power of transformer is defined from nominal range, according to condition between rated power S_{tr} and nominal calculated power S_{nom}, kVA:

$$S_{tr} \geq S_{nom} \tag{A.5.1}$$

$$S_{nom} = \frac{S_{\Sigma PV}}{N_{tr} \cdot k_{ol}} \tag{A.5.2}$$

where $S_{\Sigma PV}$ – maximum output power of invertor, kVA;

N_{tr} – the number of transformers, from paragraph Transformer substation layout;

k_{ol} – the transformer overloading coefficient, which considering possible overloading of transformer to 40%, $k_{ol} = 1.4$.

$$S_{nom} = \frac{2 \cdot 250}{1 \cdot 1.4} = 357.14$$

According to S_{nom} select transformer with rated power $S_{tr} = 400 kVA$ – ST-400, technical data of which shown at Table A.5.1.

Table A.5.1 – Parameters of three-phase, dry-insulated Solar Energy Application Transformers

Type	Rated Power, *kVA*	HV, *kV*	LV, *V*	Impedance, *%*	No-load loss, *W*
ST-400	400	12.5/25/34.5	277/480	5.9	990

A.5.2 Switchgear selection

To select switchgear, we need to know voltage level of high side and figured out number of connection elements. From the task high voltage level of connection to Power Grid is 35 *kV*. To find out number of connection firs of all calculate number of Transmission Line which needed to transmit power.

Number of Transmission Lines must be rounded up, and calculate as:

$$N_{TL} = \frac{P_{PVPP}}{P_{TC}} \qquad \text{(A.5.3)}$$

where P_{PVPP} – active Power of whole PV Power Plant, *MW*;

P_{TC} – transition capacity of Transmission Line or Power Cables, *MW*.

Table A.5.2 – Characteristics of the transmission capacity of Transmission Line

Nominal voltage, *kV*	Limited distance under efficiency 90*% per km*	transmission capacity, *MW*
35	20	15

$$N_{TL} = \frac{500}{15 \cdot 10^3} \approx 1$$

According to all this data make decision to select switchgear 35 kV “Transformer – Transmission Line”. Final draw of AC layout shown at Figure A.5.3

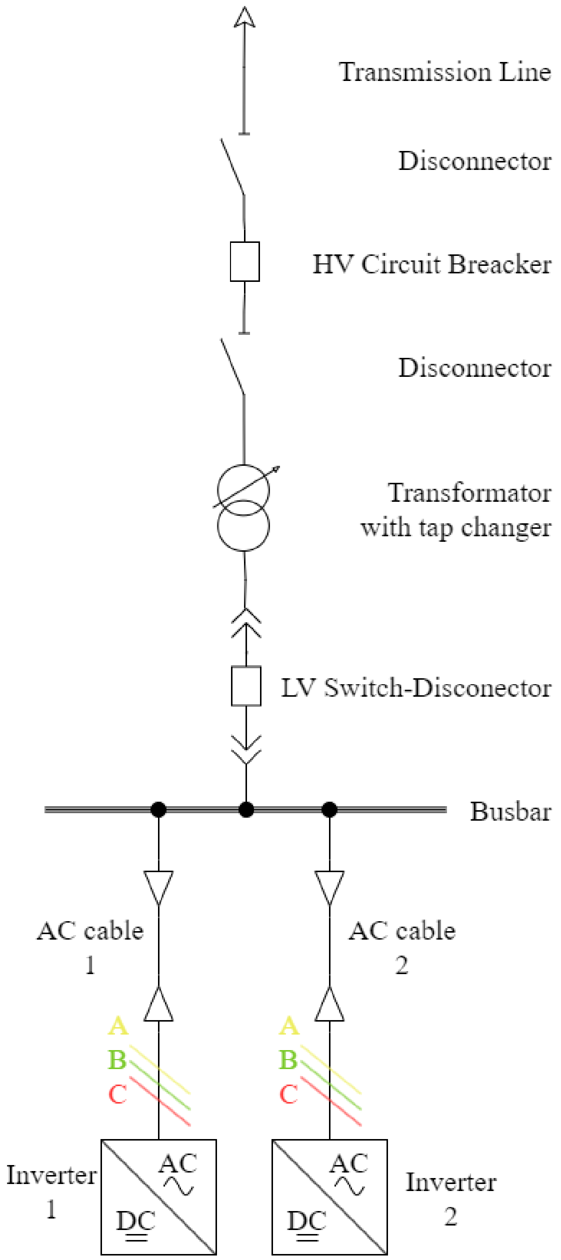


Figure A.5.3 – Design of Switchgear 35 *kV*

A.5.3 AC short circuit current

From scientific supervisor task point of Fault on Busbar.

For calculating of short circuit first step is transform Figure A.5. into Equivalent scheme (Figure A.5.4).

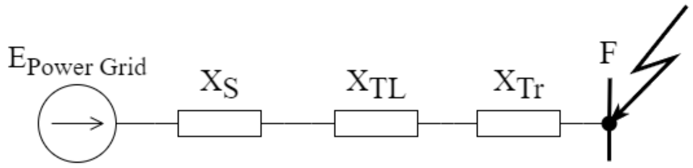


Figure A.5.4 – Equivalent scheme of PV Power Plant

To simplify Equivalent scheme needs to calculate all reactance. For this purpose, take basis power $S_{basis} = 1000\,kVA$.

The formula for system reactance is:

$$X_s = \frac{S_{basis}}{S''} \tag{A.5.4}$$

where S'' – sub-transient power of connected system (Power Grid), equal to 80000 *kVA*.

$$X_s = \frac{1000}{80\,000} = 0.01$$

The reactance of transformer calculates as following:

$$X_{Tr} = \frac{S_{basis}}{S_{r.Tr}} \cdot \frac{u_{SC}\,\%}{100\%} \tag{A.5.5}$$

where $S_{r.Tr}$ – rated power of transformer (Table A.5.1), *kVA*;

$u_{SC}\,\%$ – percentage of transformer short circuit voltage (Table A.5.1).

$$X_{Tr} = \frac{1000}{400} \cdot \frac{5.9\%}{100\%} = 0.15$$

The formula for line reactance is:

$$X_l = \frac{1}{n} \cdot x_{sp} \cdot l \cdot \frac{S_{basis}}{U_n^2} \tag{A.5.6}$$

where n – number of lines or cables;

x_{sp} – resistivity of transmission line or cable, equal to 0.4 *Ω/km* for transmission line 35 *kV*;

l – length of transmission line or cable Table A.5.2, *km*;

U_n – voltage of transmission line or cable, *kV*.

$$X_l = \frac{1}{1} \cdot 0.4 \cdot 20 \cdot \frac{1000}{35^2} = 6.53$$

Electro-motive force for Power Grid equal to 1.
Result reactance will be:

$$X_{result} = X_S + X_{tr} + X_{TL} \qquad \text{(A.5.7)}$$

$$X_{result} = 0.01 + 0.15 + 6.53 = 6.69$$

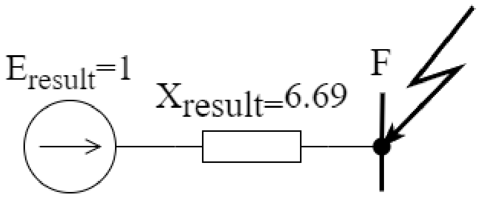


Figure A.5.5 – Simplified equivalent scheme

Effective value of the periodic component of the three-phase short circuit current at point F, *kA*:

$$I''_k = \frac{E_{result}}{X_{result}} \cdot \frac{S_{basis}}{\sqrt{3} \cdot U_n} \qquad \text{(A.5.8)}$$

$$I''_k = \frac{1}{6{,}69} \cdot \frac{1000}{\sqrt{3} \cdot 35} = 2.47$$

The peak current is calculated as, *kA*:

$$i_p = \sqrt{2} \cdot I''_k \cdot k_p \qquad \text{(A.5.9)}$$

where k_p – peak coefficient of resulting equivalent scheme equal to 1.4, depend on time constant of reducing of aperiodic d.c. short circuit component T_a=0.01.

$$i_p = \sqrt{2} \cdot 2.47 \cdot 1.4 = 4.89$$

The aperiodic d.c. component of short circuit current is calculated as follow, *kA*:

$$i_A = \sqrt{2} \cdot I''_k \cdot e^{-\tau / T_a} \qquad \text{(A.5.10)}$$

where T_a – time constant of reducing of aperiodic d.c. short circuit component;

τ – moment of time, determine by starting of disconnecting power contacts of breaker (≈0.03 *ms*) plus time of relay protection reactions (≈0.01 *ms*), taking equal to 0.04 *ms*.

$$i_A = \sqrt{2} \cdot 2.47 \cdot e^{-0.04 / 0.01} = 0.064$$

Effective value of the periodic component at moment of time τ, in case of Photovoltaic Power Plant is far-from-generator, *kA*:

$$I_{k\tau} = I''_k \qquad \text{(A.5.11)}$$

$$I_{k\tau} = 2.47$$

The thermal impulse of the three-phase short circuit current (B_k), kA^2sec, using the equation:

$$B_k = I''_k \cdot (t + T_a) \qquad \text{(A.5.12)}$$

where t – time of action of short circuit, taking equal to 0.05 *sec*.

$$B_k = 2.47 \cdot (0.05 + 0.01) = 0.15$$

A.6 SELECTING OF MAIN COMMUTATION EQUIPMENT OF AC SIDE

The main parameters of the equipment, which must meet the conditions of the working (long-term) mode, are the **nominal** *long-term current* ($I_{\max}$, *A*) and *voltage* (U_{rated} , *kV*) at level where we provide selecting.

Rated voltage is knowing, but nominal current is needed to calculate according to level where we provide selection:

On Transmission Line 35 *kV*, $I_{\max}$, *A*:

$$I_{\max} = \frac{P_{TC}}{\sqrt{3} \cdot U_{rated} \cdot \cos\varphi} \qquad \text{(A.6.1)}$$

where P_{TC} – power of transmission capacity of transmission line, *kW*;

$\cos\varphi$ – the ratio of actual power to apparent power, for power plant with DC-AC converter can be take equal to 1.

$$I_{\max} = \frac{15000}{\sqrt{3} \cdot 35 \cdot 1} = 247{,}4$$

A.6.1 Circuits-breakers

Circuit-breakers are selected according to main nominal parameters:

- by voltage:

$$U_{rated} \le U_{nom} \qquad \text{(A.6.2)}$$

where U_{nom} – nominal voltage of circuit-breaker, *kV*.

$$35 \le 35$$

- by long-term current:

$$I_{\max} \le I_{nom} \qquad \text{(A.6.3)}$$

where I_{nom} – nominal current of circuit-breaker, *A*.

$$247,4 \le 1600$$

Table A.6.1 – Outdoor circuit-breakers, SF_6 type, SF-35/2

Parameter	Type of circuit-brekers
	SF-35/2
U_{nom}, *kV*	34.5/35
I_{nom}, *A*	1600
$I_{br.c}$, *kA*	36
i_{rp}, *kA*	52
I_T, *kA*	36
t_T, sec	3
I_{MC}, *kA*	36

Checking:

- By breaking capacity of symmetrical current by condition:

$$I_{k\tau} \le I_{br.c} \qquad \text{(A.6.4)}$$

where $I_{k\tau}$ –the periodic component of short circuit current, *kA*;
$I_{br.c}$ – the breaking capacity of circuit-breaker, *kA*.

$$2.47 \le 36$$

- By breaking capacity of aperiodic d.c. component of short circuit current by condition:

$$i_A \le i_{Anom} \qquad \text{(A.6.5)}$$

where i_A –the aperiodic d.c. component of short circuit current, *kA*;
i_{Anom} – the nominal allowed value of aperiodic d.c. component of short circuit current, which breaking off at period of time τ ≈0.01 *ms*, *kA*:

$$i_{Anom} = \frac{\sqrt{2} \cdot \beta_n \cdot I_{br.c}}{100} \tag{A.6.6}$$

where β_n –the normalized value of the content of the aperiodic component in the short-circuit current, %, which is determined by the curve shown in Figure A.6.1, *pu*:

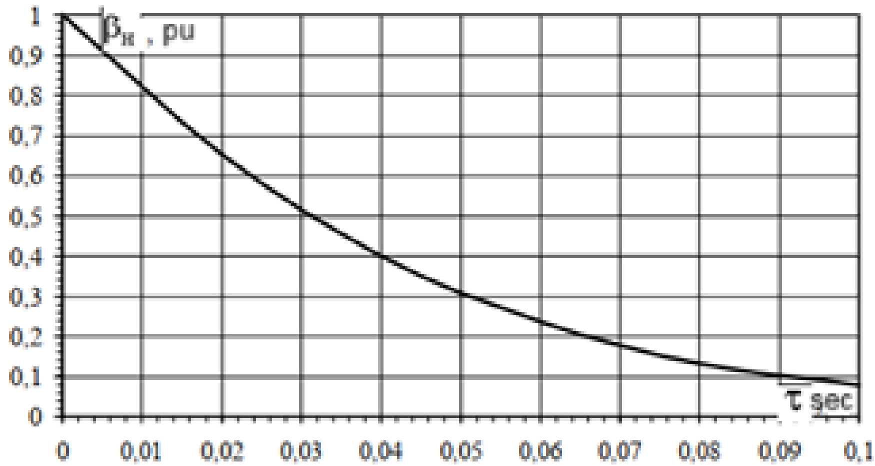


Figure A.6.1 – The normalized relative value of the aperiodic component in the short-circuit current

$$i_{Anom} = \frac{\sqrt{2} \cdot 0,82 \cdot 36}{100} = 0,418$$

$$0,064 \leq 0,418$$

Condition is fulfillment.

- By electrodynamic stability, according to limit thought out short circuit currents

$$\begin{cases} I''_k \leq I_{MC} \\ i_p \leq i_{rp} \end{cases} \tag{A.6.7}$$

where I_{MC} – the making current of circuit breaker, *kA*;

i_{rp}– rated peak withstands current of circuit breaker, *kA*.

$$\begin{cases} 2.47 \le 36 \\ 4.89 \le 52 \end{cases}$$

Condition is fulfillment.

- By thermal stability B_k, according to thermal impulse of short circuit current, kA^2t:

$$B_k \le I_T^2 \cdot t_T \qquad \text{(A.6.8)}$$

where I_T – the rms value of the short circuit current withstand duration (thermal resistance current) according to the catalog (Rated short circuit breaking current), *kA*;

t_T – withstand duration of thermal resistance current according to the catalog (rated short-time withstand duration), *sec*.

$$0.15 \le 36^2 \cdot 3 = 3888$$

All condition is fulfillment.

A.6.2 Disconnectors

Disconnectors are **selected** according to main nominal parameters:

- by voltage:

$$U_{rated} \le U_{nom} \qquad \text{(A.6.9)}$$

$$35 \le 35$$

- by long-term current:

$$I_{\max} \le I_{nom} \qquad \text{(A.6.10)}$$

$$247.4 \le 1600$$

Table A.6.2 – Outdoor disconnector parameter

Parameter	Type of disconnector
	D-35/1
U_{nom}, kV	34.5/35
I_{nom}, A	1600
i_{rp}, kA	80
I_T, kA	31.5
t_T, sec	3

Checking:

- By electrodynamic stability, according to limit thought out short circuit currents

$$i_p \le i_{rp} \tag{A.6.11}$$

$$4.89 \le 80$$

- By thermal stability B_k, according to thermal impulse of short circuit current, kA^2t:

$$B_k \le I_T^2 \cdot t_T \tag{A.6.12}$$

$$0.15 \le 31.5^2 \cdot 3 = 2976.75$$

A.6.3 Measured transformers

A.6.3.1 Measured current transformers

Measured current transformers are **selected** according to main nominal parameters:

- by voltage:

$$U_{rated} \le U_{nom} \tag{A.6.13}$$

$$35 \le 35$$

- by long-term current:

$$I_{\max} \le I_{nom} \tag{A.6.14}$$

$$247.5 \le 400$$

- By design and accuracy class: The accuracy class of current transformers according to IEC 60044-8 is chosen according to their purpose, take 0.5.

Table A.6.3 – Measured current transformer parameters

Parameter	CT-35/2
U_{nom}, kV	35
I_{nom}, A	400
$I_{secondary}$, A	1, 5
The accuracy class	0.2, 0.5, 10
Secondary load, at $cos\varphi$=0.8, VA	30
K_p	25
I_T, kA	40
t_T, sec	3

Checking:

- By electrodynamic stability, according to limit thought out short circuit currents:

$$\begin{cases} i_p \le K_p \cdot \sqrt{2} \cdot I_{1nom} \\ i_p \le i_{rp} \end{cases} \tag{A.6.15}$$

where K_p – multiplicity of electrodynamic stability according to the catalogue of current transformer;

I_{1nom} – rated primally current of current transformer, A.

$$4.89 \le 25 \cdot \sqrt{2} \cdot 5 = 176.8$$

Condition is fulfillment.

- By thermal stability B_k, according to thermal impulse of short circuit current, kA^2t:

$$\begin{cases} B_k \leq \left(K_p \cdot I_{1nom}\right) \cdot t_T \\ B_k \leq I_T^2 \cdot t_T \end{cases} \qquad (A.6.16)$$

$$0.15 \leq \left(25 \cdot 5\right) \cdot 3$$

Condition is fulfillment.

- By secondary load, Z_2:

$$Z_2 \leq Z_{2nom} \qquad (A.6.17)$$

where Z_{2nom} – nominal permissible load of the current transformer in the selected accuracy class.

$$Z_2 = r_2 + jx_2 \qquad (A.6.18)$$

.18)_where x_2 – reactive resistance of current circle, the inductive resistance is small, that is why it takes equal to 0, and $Z_2 \approx r_2$;

r_2 – active resistance of current circle, consist of resistance of connection wires r_w, transient resistance of contact elements r_c and resistance of apparatus r_{ap}:

$$r_2 = r_{ap} + r_w + r_c \qquad (A.6.19)$$

Resistance of apparatus r_{ap}, calculate as:

$$r_{ap} = \frac{S_{ap}}{I_2^2} \qquad (A.6.20)$$

where S_{ap} – power which consume by all connected apparatus, *VA*;

I_2 – secondary nominal current, according to the catalog of current transformer. *A*.

$$r_{ap} = \frac{8.3}{5^2} = 0.32$$

To calculate sum of power (S_{ap}) which consume by all connected apparatus is recommended to use table form:

Table A.6.4 – Calculation of sum of power which consume by all connected apparatus

Name and type of apparatus	Phase ***A***	Phase ***B***	Phase ***C***
Amperemeter	0.1	0.1	0.1
Electric energy meter of active and reactive power	2.5	–	2.5
Wattmeter	1	1	1
Sum:	3.6	1.1	3.6

Contact resistance r_c is taken as 0.1 Ohms.

Knowing Z_{2nom}, we determine the permissible resistance as:

$$r_w = Z_{2nom} - r_{ap} - r_c \quad \text{(A.6.21)}$$

$$r_w = 30 - 0.32 - 0.1 = 29.58$$

And needed to calculate cross-section of this wires. Cross-section must be more than 2.5 mm^2 for cooper, and less than 6 mm^2. Calculated as:

$$q = \rho \cdot \frac{l_{calc}}{r_w} \quad \text{(A.6.22)}$$

where ρ – resistivity constant of wire material, 0.0175 for cooper;

l_{calc} – calculated length, depends of current transformer connection type and distance to aparatures, taken 75 *m*.

$$q = 0.0175 \cdot \frac{75}{29.58} = 4.4$$

All condition is fulfillment.

A.6.3.2 Measured voltage transformer

Measured voltage transformers are **selected** according to main nominal parameters:

- by voltage:

$$U_{rated} \leq U_{nom} \tag{A.6.23}$$

$$35 \leq 35$$

- by configuration and scheme of winding connection.
- by accuracy class

Table A.6.5 – Measured voltage transformers

Parameter	VT-35
U_{nom}, *kV*	34.5/35
I_{nom}, *A*	1600
$U_{secondary}$, *V*	100
The accuracy class	0.2, 0.5, 10
Secondary load, at *cosφ*=0.8, *VA*	1500
I_T, *kA*	40
t_T, sec	3

Checking:

$$S_{2\Sigma} \leq S_{nom} \tag{A.6.24}$$

where S_{nom} – rated nominal power, in accordance to choose accuracy class, *VA*;

$S_{2\Sigma}$ – calculated sum of load of all measured appliance connected to voltage transformer, *VA*

Table A.6.6 – Calculation voltage transformer load

Name and type of appliance	Power of one winding of appliance, *VA*	Number of windings	$\sin\varphi$	$\cos\varphi$	Active power *P, W*	Reactive power *Q, Var*
Voltmeter	2	1	0	1	6	–
Wattmeter	1.5	2	0	1	3	–
Varmeter	2	2	0	1	12	–
Energy meter of active and reactive power	6	4	0,925	0,76	29	87,64
Frequency meter	3	1	0	1	6	–
Controlled wattmeter	10	2	0	1	20	–
Controlled voltmeter	10	2	0	1	20	–
Controlled frequency meter	10	2	0	1	10	–
Sum:	…	…	…	…	106	87.64

Calculated sum of load $S_{2\Sigma}$, *VA*:

$$S_{2\Sigma} = \sqrt{P^2 + Q^2} \tag{A.6.25}$$

$$S_{2\Sigma} = \sqrt{106^2 + 87.64^2} = 137.54$$

$$137.54 \le 1500$$

A.6.4 Flexible busbar (wires)

Flexible busbar (wires) is used to connect transformers to the outdoor switchgear. Select by:

Voltage of mechanism:

$$U_{rated} \le U_{nom} \tag{A.6.26}$$

$$35 \le 35$$

- Economic cross-section density, mm^2:

$$F_{ec} = \frac{I_{nom}}{J_{ec}} \tag{A.6.27}$$

where I_{nom} – nominal AC current of inverter, *A*;

J_{ec} – economic current density, equal 3, A/mm^2.

$$F_{ec} = \frac{247.5}{3} = 82.5$$

Table A.6.7 – Technical data of aluminum wires

Product code	Cross-section	Number and nominal diameter of wires	Max. resistance	Rated strength	Approx. overall diameter	Approx. Weight	Current carrying capacity
	mm^2	*Nox⌀*	*Ohm*	*KN*	*mm*	*Kg/km*	*Amp*
AA-95	95	19x2.5	0.3546	27.51	12.5	256	320

By flexible busbar (wire) displacement b, *m*. Determined by Figure A.6.8 in depending of ratio $\frac{f}{g}$ and $\frac{\sqrt{h}}{t_{ec}}$. Where f is the force from the long-term current of short-circuit (*N/m*); g is gravitation force (*N/m*); h is the maximum design sag in each run at the maximum design temperature (*m*), not more than 2 – 2.5 *m* for outdoor switchgear; t_{ec} is pulse-equivalent action time of fast-acting protection (*sec*), takes equal to 0.15 *sec*. $\frac{\sqrt{h}}{t_{ec}} = \frac{\sqrt{2}}{0.15} = 9.43$

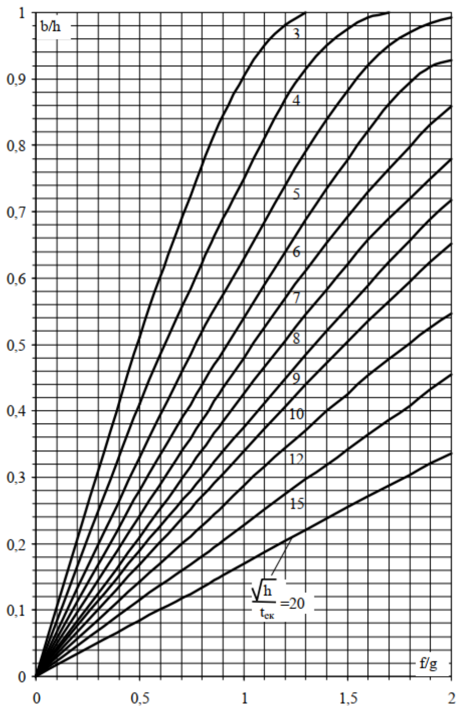


Figure A.6.2 – Displacement diagram of a flexible current conductor with horizontal arrangement of phases under the action of short-circuit currents

Found displacement b compare with maximal acceptable b_{ac}:

$$b < b_{ac} = \frac{D - d - a_{ac}}{2} \tag{A.6.28}$$

where D – distance between phases (Table A.6.), *m*;
d – diameter of flexible busbar (wire), *m*.

$$\frac{b}{2} = 0.12 \rightarrow b = 0.24$$

$$0.24 < b_{ac} = \frac{1.5 - 0.0029 - 0}{2} = 0.75$$

Condition is fulfillment.

- The force from the long-term current of short-circuit is determined, *N/m*:

$$f = 0.15 \cdot \frac{\left(I_k''\right)^2}{D} \tag{A.6.29}$$

$$f = 0.15 \cdot \frac{\left(2.47\right)^2}{1.5} = 0.61$$

Table A.6.9 – Parameters D and a_{add}

Parameter	Flexible busbar (wires) of outdoor switchgear, *kV*
	35
D, m	1.5
a_{add}, *m*	–

Gravitation force on 1 *m* of flexible busbar (wires), *N/m*:

$$g = 9.8 \cdot m \tag{A.6.30}$$

where m – weight for 1 *m*.

$$g = 9.8 \cdot 247 = 2420.6$$

$$\frac{f}{g} = \frac{0.61}{2420.6} = 0.25$$

Flexible busbars (wires) with split phases are also checked for electrodynamic interaction of conductors of one phase.

- The force on each wire from the interaction with the remaining n-1 wires, *N/m*:

$$f_c = \frac{n-1}{n^2} \cdot 0.2 \cdot \frac{\left(I_k''\right)^2}{d} \tag{A.6.31}$$

where n – number of wires at each phase.

$$f_c = \frac{19-1}{19^2} \cdot 0.2 \cdot \frac{\left(2.47\right)^2}{2.5} = 0.025$$

- Corona testing:

$$1{,}07 \cdot E \le 0.9 \cdot E_0 \tag{A.6.32}$$

A discharge in the form of a corona occurs at the maximum value of the initial critical intensity of the electric field, *kV/cm*:

$$E_0 = 30.3 \cdot 0.82 \cdot \left(1 + \frac{0.299}{\sqrt{2.5}}\right) = 29.54 \tag{A.6.33}$$

where m – coefficient that takes into account the roughness of the wire surface, equal 0.82;

r_0 – wire radius, *cm*.

$$E_0 = 30.3 \cdot m \cdot \left(1 + \frac{0.299}{\sqrt{r_0}}\right)$$

Electric field strength (maximum value) near the surface of unsplit or near split wires, *kV/cm*:

$$E = K \cdot \frac{0.354 \cdot U_{\max}}{n \cdot r_0 \cdot \lg \frac{D_{av}}{r_{ek}}} \qquad \text{(A.6.34)}$$

where K – coefficient that takes into account the number of wires in a phase;

$U_{\max}$ – maximum permissible installation voltage, *kV*;

n – number of wires at each phase;

D_{av} – the average geometric distance between the phase wires, *cm* (with the horizontal arrangement of the phases $D_{av} = 1.26 \cdot D$);

r_{ek} – equivalent radius of split wires, *cm*

Table A.6.10 – Parameters K and r_{ek}

Parameter	number of wires at each phase			
	1	2	3	4
K	1	$1+2\cdot\frac{r_0}{a}$	$1+2\cdot\sqrt{3}\cdot\frac{r_0}{a}$	$1+3\cdot\sqrt{2}\cdot\frac{r_0}{a}$
r_{ek}	r_0	$\sqrt{r_0 \cdot a}$	$\sqrt[3]{r_0 \cdot a^2}$	$\sqrt[4]{\sqrt{2} \cdot r_0 \cdot a^3}$

$$E = 1 \cdot \frac{0.354 \cdot 35}{19 \cdot 2.5 \cdot \lg \frac{1.26 \cdot 1.5}{2.5}} = 9.6$$

$$1{,}07 \cdot 9.6 = 10.27 \le 0.9 \cdot 29.54 = 26.59$$

All condition is fulfillment.

A.7 DRAWING PART

Drawing part can be named as graphical conclusion of all calculation. At FigureA.7.1 shown complete drawing according to task of example

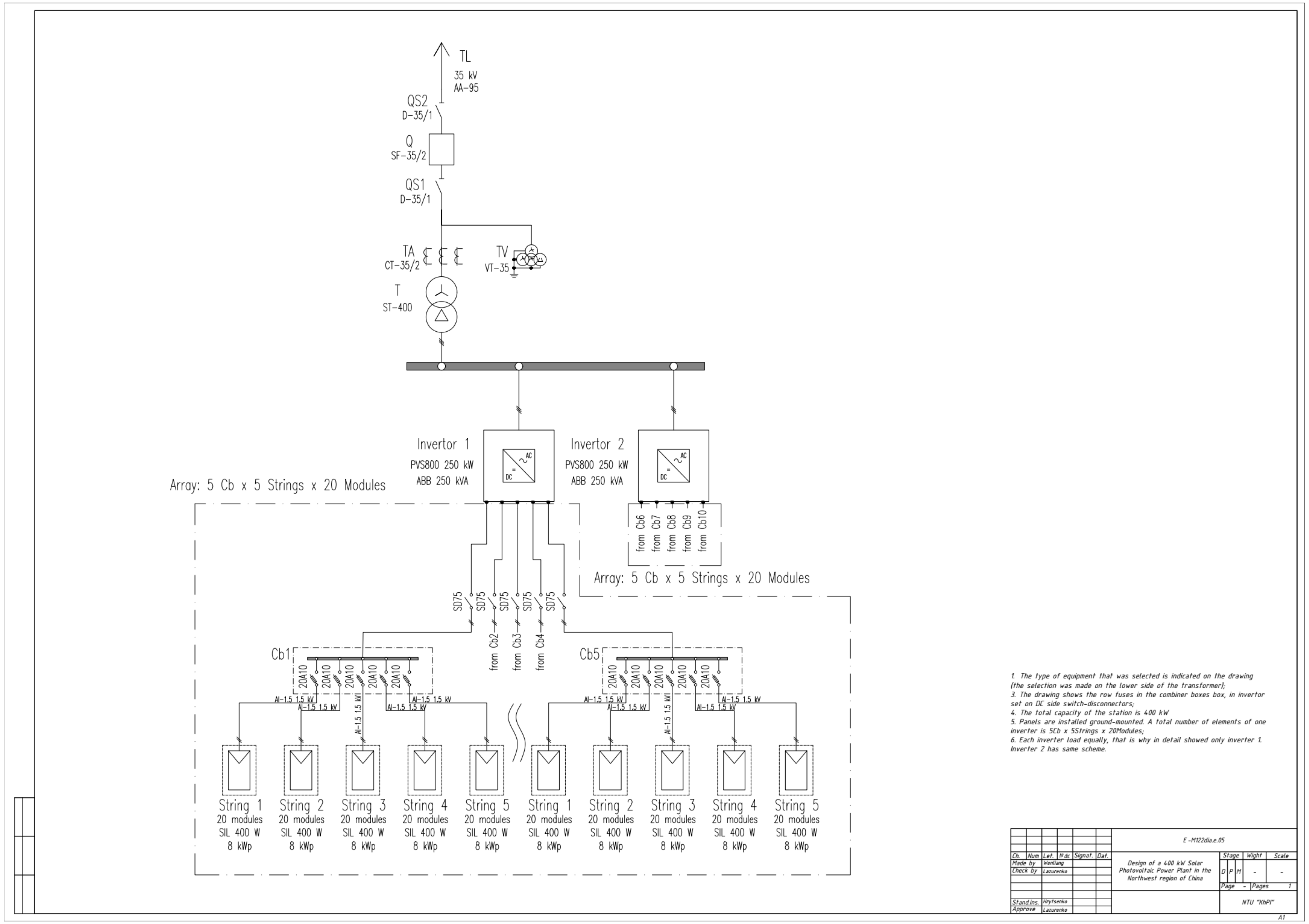


Figure A.7.1 – Dodatok / Complete drawing

A.8 REFERENCES

1. Misconceptions About China [Electronic resource] // Acton Institute. 2024. URL: https://www.acton.org/audio/misconceptions-about-china (accessed: 24.04.2024).
2. McElroy M. et al. Potential for Wind-Generated Electricity in China // Science. 2009. Vol. 325. P. 1378–1380.
3. Yuan J. Coal Power Economics in China. 2016.
4. Global Coal Plant Tracker [Electronic resource] // Global Energy Monitor. 2023. URL: https://globalenergymonitor.org/projects/global-coal-plant-tracker/ (accessed: 24.04.2024).
5. Bahach U. et al. Prospects for Solar Energy Development in Belarus and Tatarstan: 24 // Energies. Multidisciplinary Digital Publishing Institute, 2021. Vol. 14, № 24. P. 8491.
6. Nations U. What is renewable energy? [Electronic resource] // United Nations. United Nations. URL: https://www.un.org/en/climatechange/what-is-renewable-energy?gad_source=1&gclid=CjwKCAjw26KxBhBDEiwAu6KXtwW1QCEpqR1qcb5OxuGsBi5BYoYBYkBK_v2Tfb5EY6vZuXk7JlAT6hoC_s4QAvD_BwE (accessed: 24.04.2024).
7. Clean Energy for America Education Fund [Electronic resource] // Clean Energy for America Education Fund. 2024. URL: https://ce4aef.org (accessed: 24.04.2024).
8. MODIS/Terra+Aqua Land Cover Type Yearly L3 Global 500m SIN Grid - LAADS DAAC [Electronic resource]. URL: https://ladsweb.modaps.eosdis.nasa.gov/missions-and-measurements/products/MCD12Q1/ (accessed: 24.04.2024).
9. Open Energy Transition [Electronic resource]. URL: https://openenergytransition.org/?gad_source=1&gclid=CjwKCAjw26KxBhBDEiwAu6KXtxIqeOcif6UEyI_rRWCR0ocTMdZgZ_Q1z8Y2gXvwJ7Ptcj60EzATlRoC1UcQAvD_BwE (accessed: 24.04.2024).
10. Foresight Review on the Future of Regulatory Systems [Electronic resource] // Lloyd’s Register Foundation. URL: https://www.lrfoundation.org.uk/en/publications/download-foresight-review-on-regulation/ (accessed: 24.04.2024).

11. He G., Kammen D. Where, when and how much solar is available? A provincial-scale solar resource assessment for China // Renew. Energy. 2016. Vol. 85. P. 74–82.

12. Carrion M., Arroyo J. A Computationally Efficient Mixed-Integer Linear Formulation for the Thermal Unit Commitment Problem // Power Syst. IEEE Trans. On. 2006. Vol. 21. P. 1371–1378.

13. Learn about Wind Harvest - Netcapital [Electronic resource]. URL: http://netcapital.com/companies/windharvest (accessed: 24.04.2024).

14. RELP, Renewable energy for all. [Electronic resource] // RELP. URL: https://www.relp.ngo/ (accessed: 24.04.2024).

15. Global Solar Atlas [Electronic resource]. URL: https://globalsolaratlas.info/support/getting-started (accessed: 24.04.2024).

16. POWER | Data Access Viewer [Electronic resource]. URL: https://power.larc.nasa.gov/data-access-viewer/ (accessed: 24.04.2024).

17. Silfab Solar NU Series SIL-400 NU | EnergySage [Electronic resource]. URL: https://www.energysage.com/solar-panels/silfab-solar/2513/sil-400-nu/ (accessed: 24.04.2024).

18. Buy Solar Inverter ABB PVS800-250kW | pvXchange.com [Electronic resource] // Buy Solar Inverter ABB PVS800-250kW | pvXchange.com. URL: https://www.pvxchange.com/Solar-Inverters/ABB/PVS800-250kW_1-2301259 (accessed: 24.04.2024).

19. Technical Application Papers [Electronic resource] // Low Voltage Products. URL: https://new.abb.com/low-voltage/pt-pt/products/technical-application-papers (accessed: 19.04.2024).

20. Pile Ground Mounting System For Solar System Manufacturers and Suppliers China - Factory Price - Wanhos [Electronic resource]. URL: https://www.wanhossolars.com/ground-mounting-system/pile-ground-mounting-system-for-solar-system.html (accessed: 24.04.2024).

21. POWERFLEX RV-K — ТОВ «АБСЕЛ» [Electronic resource]. URL: https://absel.ua/kabelnaja-produkcija/cilovye-kabeli-do-1kv/powerflex-rv-k.html (accessed: 19.04.2024).

22. Search results | IEC Webstore [Electronic resource]. URL: https://webstore.iec.ch/searchform&q=IEC%2060076 (accessed: 24.04.2024).

23. IEC 60909-0:2016 | IEC Webstore [Electronic resource]. URL: https://webstore.iec.ch/publication/24100 (accessed: 24.04.2024).

24. IEC 60320-2-1:2018 | IEC Webstore [Electronic resource]. URL: https://webstore.iec.ch/publication/33701 (accessed: 24.04.2024).

APPENDIX B
EQUIPMENT

B.1 Inverters

B.1.1 ABB string inverters PVS300 3.3 to 8.0 *kW*

Inverters for Small-Residential solution

String inverters cost-effectively convert the direct current generated by solar panels into high-quality alternating current that can be fed into the power network. Designed to meet the needs of the entire supply chain – from system integrators and installers to end users – these transformerless, single-phase inverters are suitable for small and medium-size photovoltaic systems connected to the public electricity network.

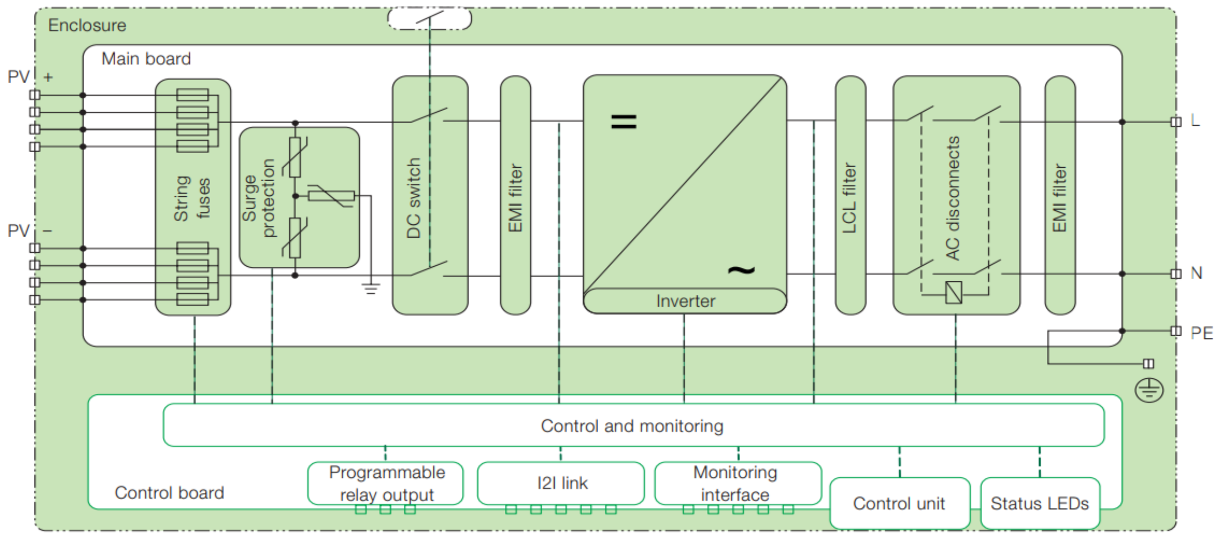


Figure B.1 – ABB string inverter design and grid connection

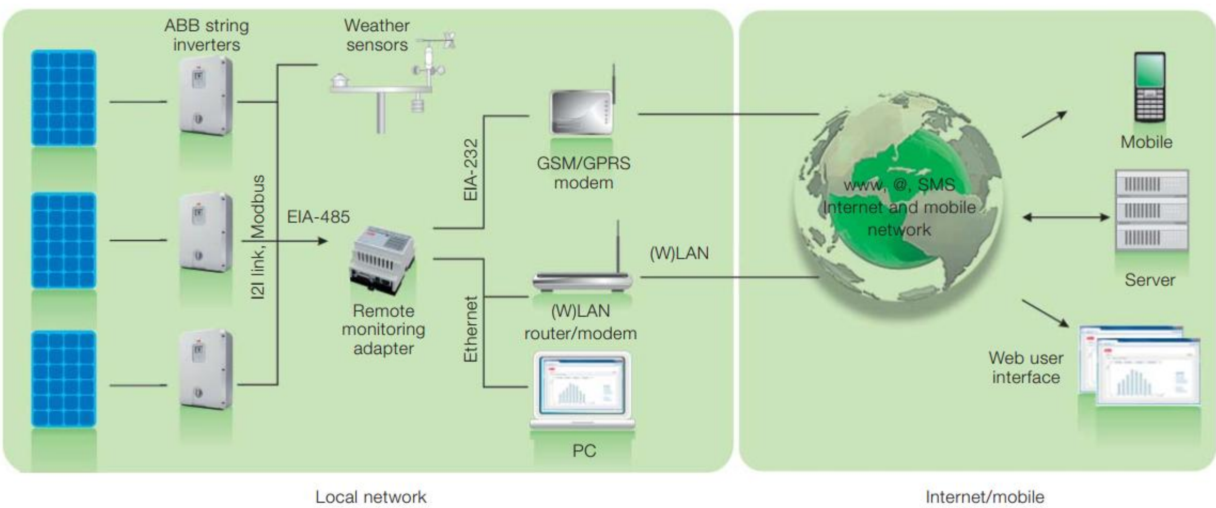


Figure B.2 – ABB string inverter data communication principle

Intuitive control unit with versatile mounting options:

The simplicity of the control unit enables a fast inverter set-up. The control unit can be mounted within the inverter enclosure or alternatively it comes with an optional wall mounting kit which enables it to be installed away from the actual inverter, for example on a wall inside the building. From here the user can monitor the inverter performance round-the-clock.

Table B.1 –ABB String Inverters PVS300 3.3 to 8.0 kW

Type / Parameter	PVS300-TL-3300W-2	PVS300-TL-4000W-2	PVS300-TL-4600W-2	PVS300-TL-6000W-2	PVS300-TL-8000W-2
Input (DC)					
Nominal PV-power (P_{PV})	3400 *W*	4100 *W*	4700 *W*	6100 *W*	8100 *W*
Maximum PV-power ($P_{PV,max}$)	3700 *W*	4500 *W*	5200 *W*	6700 *W*	8900 *W*
DC voltage range, mpp (U_{DC})	335 to 800 V				
Max DC voltage ($U_{DC,\ max}$)	900 V				
Nominal DC voltage, (U_N)	480 V				
Max DC current ($I_{DC,\ max}$)	10.5 *A*	12.7 *A*	14.6 *A*	19.0 *A*	25.4 *A*
Number of DC inputs (parallel)	4, with MC4 quick connectors				
Output (AC)					
Nominal AC output power (P_{AC})	3300 W	4000 W	4600 W	6000 W	8000 W
Nominal AC current ($I_{AC,\ nom}$)	14.3 *A*	17.4 *A*	20.0 *A*	26.1 *A*	34.8 *A*
Nominal voltage ($V_{AC,\ nom}$)	230 V				
Operating range, grid voltage	180 to 276 *V*				
Operating range, grid frequency (f_{AC})	47 to 63 *Hz*				
Harmonic distortion of grid current (K_{IAC})	< 3%				
Power factor ($\cos\varphi$)	1				
Grid connection	Single phase: *L*, *N* and *PE*				
Transformer	No				
Efficiency					
Max efficiency (P_{ACmax})	97.1 %				
Euro-eta	96.0 %	96.3 %	96.3 %	96.6 %	96.6 %
Power consumption					
In standby operation ($P_{standby}$)	< 12 *W*				
Night consumption (P_{night})	< 1 *W*				
Environmental limits					
Permissible ambient temperature range	-25 *C*° to +60 *C*°				
Degree of protection	IP55				
Dimensions and weight					
Width / Height / Depth	*W* = 392 mm / *H* = 581 mm / *D* = 242 mm				

B.1.2 ABB central inverters

B.1.2.1 PVS800 100 to 1000 kW

ABB central inverters raise reliability, efficiency and ease of installation to new levels. The inverters are aimed at system integrators and end users who require high performance solar inverters for large photovoltaic (PV) power plants. The inverters are available from 100 up to 1000 kW, and are optimized for cost-efficient multimegawatt power plants

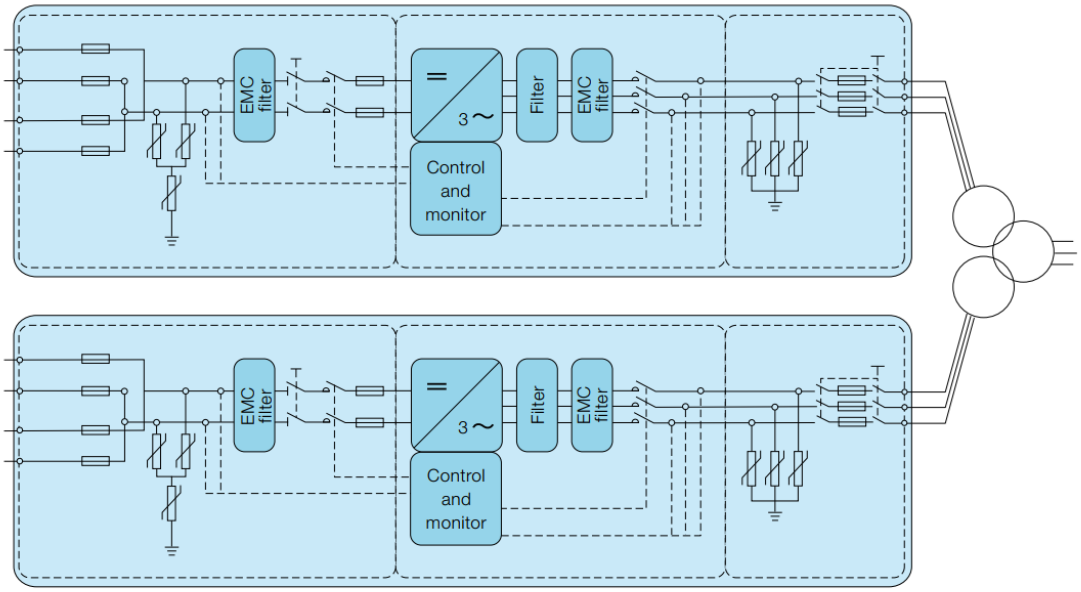


Figure B.3 – ABB PVS800 100 to 1000 kW central inverter design and power network connection

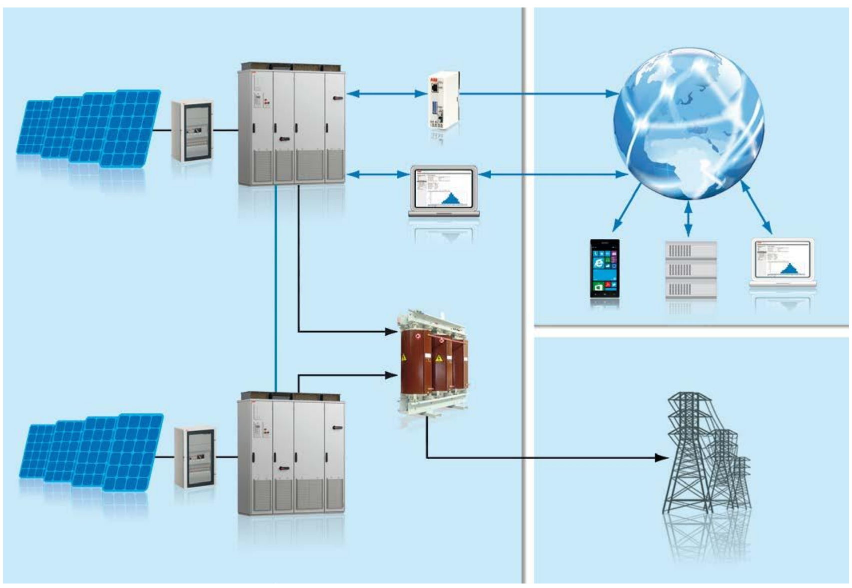


Figure B.4 – Data communication principle for ABB central inverters

Table B.2 – ABB central inverters PVS800 100 to 315 kW

Type / Parameter	PVS800-57-0100kW-A	PVS800-57-0250kW-A	PVS800-57-0315kW-A
Input (DC)			
Maximum input power ($P_{PV, max}$)	120 *kWp*	300 *kWp*	378 *kWp*
DC voltage range, mpp ($U_{DC, mpp}$)	450 to 825 *V*		525 to 825 *V*
Maximum DC voltage ($U_{max (DC)}$)	1000 *V*		
Maximum DC current ($I_{max (DC)}$)	245 *A*	600 *A*	615 *A*
Number of protected DC inputs	1 *(+/-)* /4	2, 4, 8 *(+/-)*	
Output (AC)			
Nominal power ($P_{N(AC)}$)	100 *kW*	250 *kW*	315 *kW*
Maximum output powe	100 *kW*	250 *kW*	345 *kW*
Power at cosφ = 0.95	96 *kV*	240 *kW*	300 *kW*
Nominal AC current ($I_{N(AC)}$)	195 *A*	485 *A*	520 *A*
Nominal output voltage ($U_{N(AC)}$)	300 *V*		350 *V*
Output frequency	50/60 *Hz*		
Harmonic distortion, current	< 3%		
Distribution network type	*TN* and *IT*		
Efficiency			
Maximum	98.0 %		98.6 %
Euro-eta	97.5 %	97.6 %	98.3 %
Power consumption			
Own consumption in operation	310 *W*		
Standby operation consumption	60 *W*		
Environmental limits			
Ambient temp. range (nom. ratings)	-15 to +40 *°C*		
Degree of protection	IP 42		
Dimensions and weight			
Width/Height/Depth, mm	1030/2130/690	1830/2130/680	1830/2130/680
Protection			
Ground fault monitoring	YES		
Grid monitoring	YES		
Anti-islanding	YES		
DC reverse polarity	YES		
AC and DC short circuit and over current	YES		
AC and DC over voltage and temperature	YES		

Table B.3 – ABB central inverters PVS800 500 to1000 kW

Parameter \ Type	PVS800-57-0500kW-A	PVS800-57-0630kW-A	PVS800-57-0875kW-A	PVS800-57-1000kW-A
Input (DC)				
Maximum input power ($P_{PV,\ max}$)	600 *kWp*	756 *kWp*	1050 *kWp*	1200 *kWp*
DC voltage range, mpp ($U_{DC,\ mpp}$)	450 to 825 *V*	525 to 825 *V*		600 to 850 *V*
Maximum DC voltage ($U_{max\ (DC)}$)	1100 *V*			
Maximum DC current ($I_{max\ (DC)}$)	1145 *A*	1230 *A*	1710 *A*	
Number of protected DC inputs	4 to 15 *(+/-)*		8 to 20 *(+/-)*	
Output (AC)				
Nominal power ($P_{N(AC)}$)	500 *kW*	630 *kW*	875 *kW*	1000 *kW*
Maximum output powe	600 *kW*	700 *kW*	1050 *kW*	1200 *kW*
Power at cosφ = 0.95	475 *kW*	600 *kW*	830 *kW*	950 *kW*
Nominal AC current ($I_{N(AC)}$)	965 *A*	1040 *A*	1445 *A*	
Nominal output voltage ($U_{N(AC)}$)	300 *V*	350 *V*		400 *V*
Output frequency	50/60 *Hz*			
Harmonic distortion, current	< 3%			
Distribution network type	*TN* and *IT*			
Efficiency				
Maximum	98.6 *%*		98.7 *%*	98.8 *%*
Euro-eta	98.2 *%*	98.4 *%*	98.5 *%*	98.6 *%*
Power consumption				
Own consumption in operation	490 *W*		650 *W*	
Standby operation consumption	65 *W*			
Environmental limits				
Ambient temp. range (nom. ratings)	-15 to +40 *°C*			
Degree of protection	IP 42			
Dimensions and weight				
Width/Height/Depth	2630/2130/708	2630/2130/708	3630/2130/708	3630/2130/708
Protection				
Ground fault monitoring	YES			
Grid monitoring	YES			
Anti-islanding	YES			
DC reverse polarity	YES			
AC and DC short circuit and over current	YES			
AC and DC over voltage and temperature	YES			

B.1.2.2 ULTRA-700/1050/1400/1500-TL OUTD 780 to 1560 kW

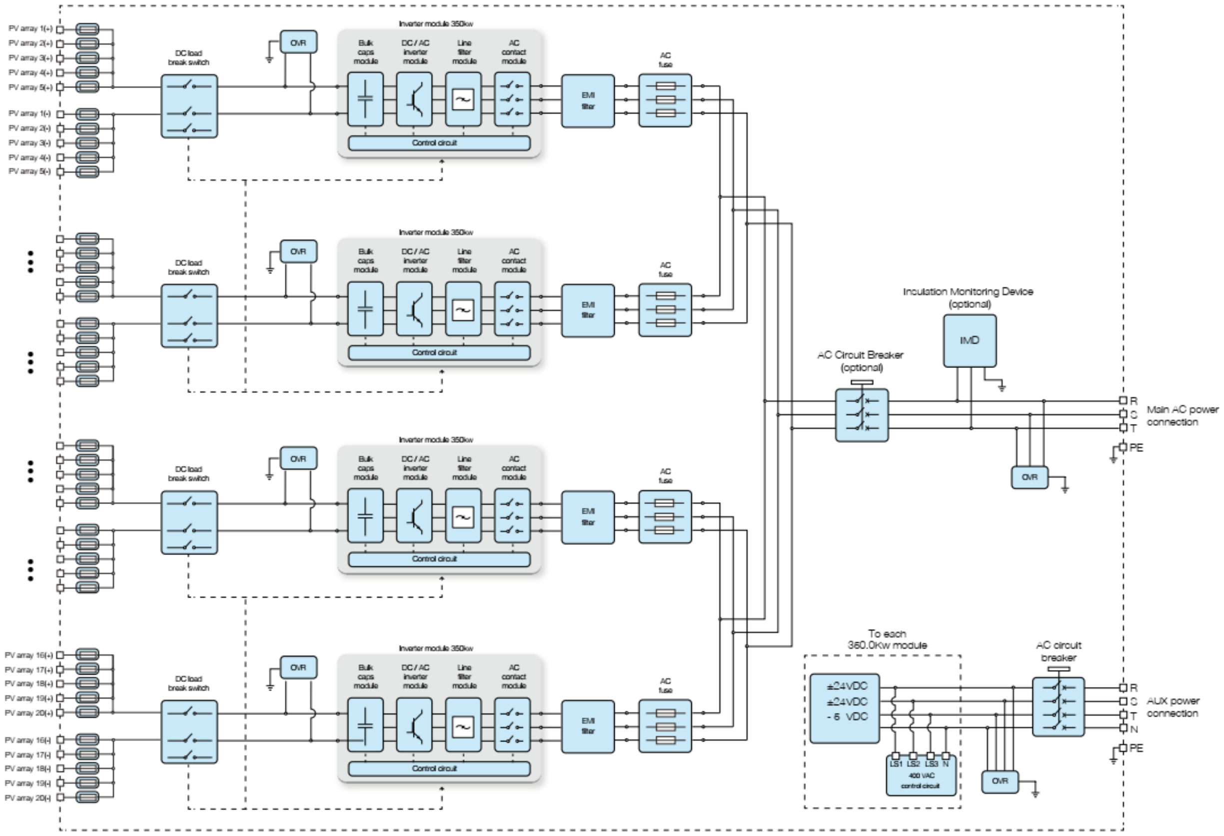


Figure B.5 – Block diagram of ULTRA

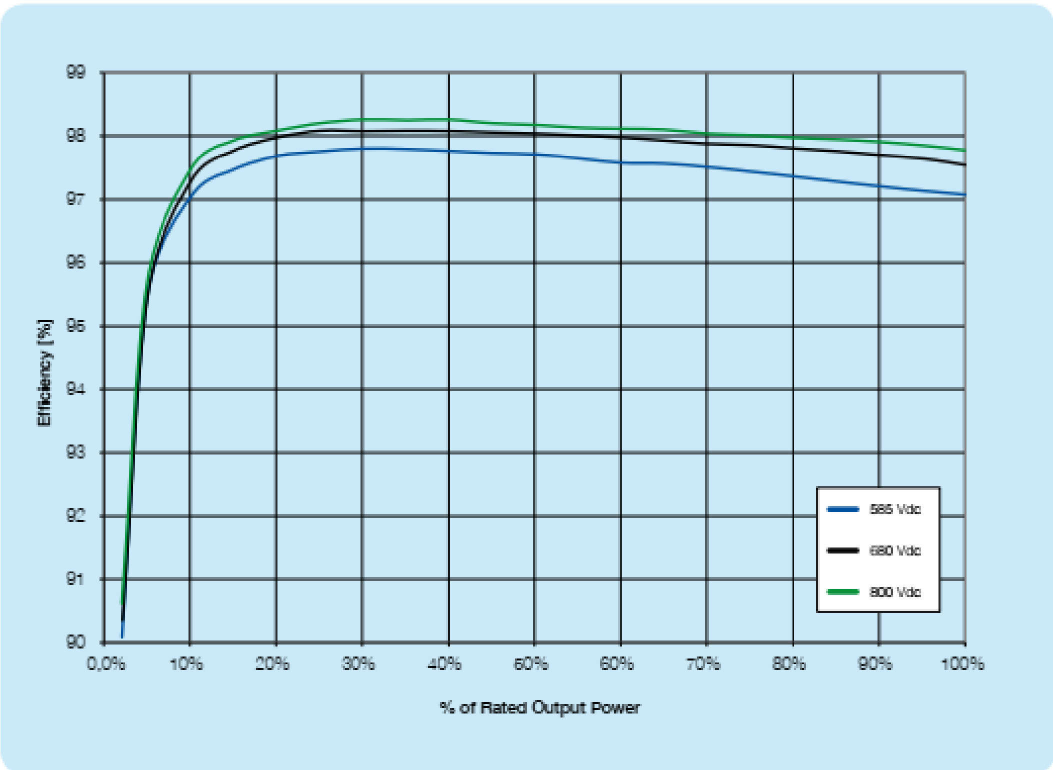


Figure B.6 – Efficiency curves of ULTRA

Table B.4 – ULTRA-700.0/1050.0/1400.0/1500.0-TL OUTD 780 to 1560 kW

Parameter \ Type	ULTRA-700.0-TL	ULTRA-1050.0-TL	ULTRA-1400.0-TL	ULTRA-1500.0-TL
Input (DC)				
Absolute maximum DC input voltage ($V_{max,abs}$)	1000 *V*			
MPPT input DC voltage range ($V_{MPPTmin}$ ... $V_{MPPTmax}$) at V_{acr}	470...900 *V*			
MPPT input DC range ($V_{MPPTmin}$ ... $V_{MPPTmax}$) at P_{acr} and V_{acr}	585...850 *V* at V_{acr} 645...850 *V* at P_{acr}			
Number of independent MPPT multi-master	2	3	4	
Maximum DC input current for each module ($I_{dcmax,m}$)	694 *A*			
Number of DC inputs pairs	10	15	20	
Output (AC)				
Maximum apparent power (S_{max})	780 *kVA*	1170 *kVA*	1560 *kVA*	
Rated AC power (P_{acr} *at* cosφ = 1)	780 *kW*	1170 *kW*	1560 *kW*	
Rated grid voltage (V_{acr})	690 *V*			
AC voltage range (V_{acmin}...V_{acmax})	621 to 759 *V*			
Maximum output current (I_{acmax})	650 *A*	975 *A*	1300 *A*	
Contributory fault current	1036 *A*	1554 *A*	2072 *A*	
Rated frequency (f_r)	50/60 *Hz*			
Frequency range (f_{min}...f_{max})	47 to 53 / 57 to 63 *Hz*			
Total harmonic distortion	< 3% (@ $P_{ac,r}$)			
Efficiency				
Maximum	98.7 %			
Euro-eta	98.2 %			
Power consumption				
Own consumption in operation	< 0.50% of $P_{ac,r}$	< 0.60% of $P_{ac,r}$	< 0.50% of $P_{ac,r}$	
Standby operation consumption	< 90 *W*	< 110 *W*	< 180 *W*	
Environmental limits				
Ambient temp. range	-20 to + 60 *°C* with derating above 50 *°C*			
Degree of protection	IP 65			IP 54
Dimensions and weight				
Width/Height/Depth	2920/3020/1520			2734/4840/1128
Protection				
Ground fault monitoring	YES			
Grid monitoring	YES			
Anti-islanding	YES			
DC reverse polarity	YES			
AC and DC SC and OC	YES			
AC and DC over voltage and temperature	YES			

B.1.2.3 PVS980 1818 to 2000 kVA

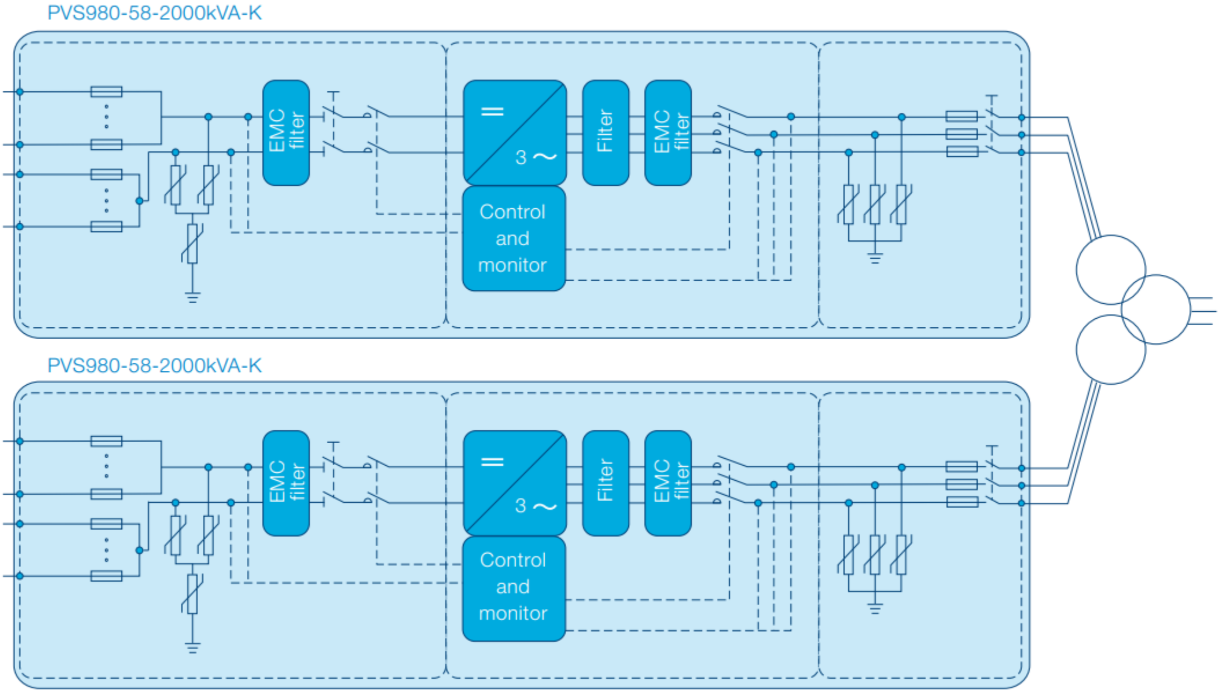


Figure B.7 – ABB PVS980 central inverter design and power network connection

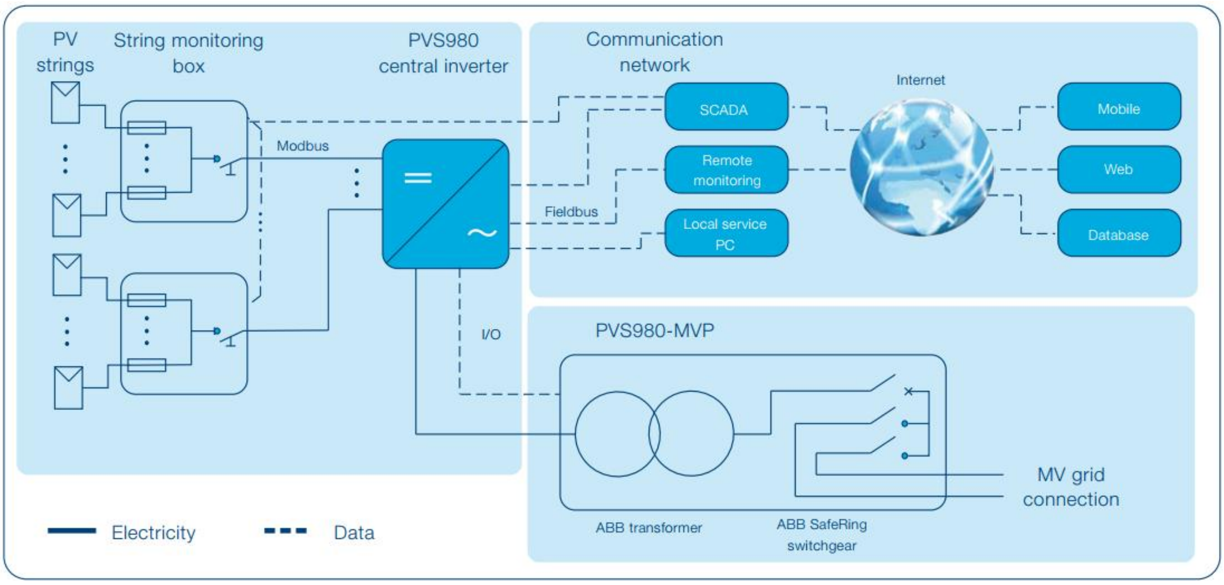


Figure B.8 – Data communication principle for ABB PVS980 central inverters

ABB central inverters raise reliability, efficiency and ease of installation to new levels. The inverters are aimed at system integrators and end users who require highperformance solar inverters for large photovoltaic (PV) power plants. PVS980 central inverters are available from 1818 kVA up to 2000 kVA, and are optimized for costeffective, multi-megawatt power plants.

Table B.5 – ABB central inverters PVS980 1818 to 2000 kVA

Parameter \ Type	PVS980-58-1818kVA-I	PVS980-58-1909kVA-J	PVS980-58-2000kVA-K
Input (DC)			
Maximum input power ($P_{PV, max}$)	2910 *kWp*	3055 *kWp*	3200 *kWp*
DC voltage range, mpp ($U_{DC, mpp}$) at 50 °C	850 to 1100 *V*	893 to 1100 *V*	935 to 1100 *V*
DC voltage range, mpp ($U_{DC, mpp}$) at 35 °C	850 to 1500 *V*	893 to 1500 *V*	935 to 1500 *V*
Maximum DC voltage ($U_{max (DC)}$)	1500 *V*		
Number of MPPT trackers	1		
Number of protected DC inputs	8 to 24 *(+/-)*		
Output (AC)			
Nominal power ($S_{N(AC)}$)	1818 *kVA*	1909 *kVA*	2000 *kVA*
Maximum output power ($S_{max (AC)}$)	2000 *kVA*	2100 *kVA*	2200 *kVA*
Nominal AC current ($I_{N(AC)}$)	1750 *A*		
Nominal output voltage ($U_{N(AC)}$)	600 *V*	630 *V*	660 *V*
Output frequency	50/60 *Hz*		
Harmonic distortion, current	< 3%		
Distribution network type	*TN* and *IT*		
Efficiency			
Maximum	98.8 %		
Euro-eta	98.6%		
Power consumption			
Own consumption in operation	2500 *W*		
Standby operation consumption	225 *W*		
Environmental limits			
Ambient temp. range (nom. ratings)	-20 to +50 *°C*		
Degree of protection	IP65 / Type 4X		
Dimensions and weight			
Width/Height/Depth, mm	3180/2366/1522		
Protection			
Ground fault monitoring	YES		
Grid monitoring	YES		
Anti-islanding	YES		
DC reverse polarity	YES		
AC and DC short circuit and over current	YES		
AC and DC over voltage and temperature	YES		

B.2 Photovoltaic panels

B.2.1 Silfab SOLAR

Table B.6 – Silfab SOLAR series SLA-M 285 to 300 *W*

Parameter \ Type		SLA-M 285	SLA-M 290	SLA-M 300	SLA-M 310	SLA-M 320	SLA-M 350	SLA-M 360	SLA-M 370
Electrical specifications									
Module Power (P_{max})	*Wp*	285	290	300	310	320	350	360	370
Maximum power voltage (V_{pmax})	*V*	32.0	32.4	32.8	33.05	33.7	38.9	39.3	39.6
Maximum power current (I_{pmax})	*A*	8.91	8.97	9.16	9.38	9.5	9.02	9.20	9.35
Open circuit voltage (V_{oc})	*V*	39.1	39.4	39.85	40.25	40.45	47.5	47.9	48.2
Short circuit current (I_{sc})	*A*	9.47	9.54	9.71	9.93	9.96	9.61	9.71	9.93
Module efficiency	*%*	17.4	17.8	18.4	19.0	19.6	17.9	18.5	19.0
Maximum system voltage (V_{DC})	*V*	1000							
Series fuse rating	*A*	20							
Power Tolerance	*Wp*	-0/+5							
Temperature ratings									
Temperature Coefficient I_{sc}	*%/K*	0.03							
Temperature Coefficient V_{oc}	*%/K*	-0.30							
Temperature Coefficient P_{max}	*%/K*	-0.38							
NOCT (± 2°*C*)	*°C*	45							
Operating temperature	*°C*	-40/+85							
Mechanical properties / Components									
Module weight	*kg*	19					23		
Dimensions (*H* / *L* / *D*)	*mm*	1650 / 990 / 38					1970 / 990 / 38		

Table B.7 – Silfab SOLAR series SIL 300 to 370 *W*

Parameter \ Type		SIL- 300	SIL- 310	SIL- 320	SIL- 330 BL	SIL- 330 HC	SIL- 330	SIL- 370	SIL- 370
Electrical specifications									
Module Power (P_{max})	*Wp*	300	310	320	330	330	330	370	370
Maximum power voltage (V_{pmax})	*V*	32.8	33.05	34.36	34.72	33.7	33.3	38.34	38.1
Maximum power current (I_{pmax})	*A*	9.16	9.38	9.32	9.51	9.8	9.92	9.69	9.7
Open circuit voltage (V_{oc})	*V*	39.85	40.25	42.04	42.24	40.1	40.5	44.76	47.5
Short circuit current (I_{sc})	*A*	9.71	9.93	9.77	9.83	10.4	10.42	10.33	9.9
Module efficiency	*%*	17.6	18.2	18.84	19.4	19.4	19.4	20.8	18.7
Maximum system voltage (V_{DC})	*V*	1000							
Series fuse rating	*A*	20							
Power Tolerance	*Wp*	0/+5							
Temperature ratings									
Temperature Coefficient I_{sc}	*%/C*	0.064		0.046		0.064		0.046	0.03
Temperature Coefficient V_{oc}	*%/C*	-0.28		-0.279		-0.28		-0.279	-0.3
Temperature Coefficient P_{max}	*%/C*	-0.36		-0.377		-0.36		-0.377	-0.38
NOCT (± 2°*C*)	*°C*	45		43.5		46		43.5	44
Operating temperature	*°C*	-40/+85							
Mechanical properties / Components									
Module weight	*kg*	18.6		18.2		18.6		19	21.5
Dimensions (*H* / *L* / *D*)	*mm*	1700/1000/38		1700/1000/38		1700/1000/38		1795/990/38	1992/994/38

Table B.8 – Silfab SOLAR series SIL 380 to 490 *W*

<table>
<tr><th colspan="2">Parameter \ Type</th><th>SIL- 380</th><th>SIL- 390</th><th>SIL- 400</th><th>SIL- 410</th><th>SIL- 410 HC</th><th>SIL- 420</th><th>SIL- 430</th><th>SIL- 490</th></tr>
<tr><td colspan="10">Electrical specifications</td></tr>
<tr><td>Module Power (P_{max})</td><td>Wp</td><td>380</td><td>390</td><td>400</td><td>410</td><td>410</td><td>420</td><td>430</td><td>490</td></tr>
<tr><td>Maximum power voltage (V_{pmax})</td><td>V</td><td>38.67</td><td>39.25</td><td>36.05</td><td>38.99</td><td>38.07</td><td>33.08</td><td>33.25</td><td>45.23</td></tr>
<tr><td>Maximum power current (I_{pmax})</td><td>A</td><td>9.85</td><td>9.95</td><td>11.10</td><td>10.52</td><td>10.77</td><td>12.70</td><td>12.93</td><td>10.83</td></tr>
<tr><td>Open circuit voltage (V_{oc})</td><td>V</td><td>47.88</td><td>48.3</td><td>43.02</td><td>45.59</td><td>45.92</td><td>38.84</td><td>38.91</td><td>52.96</td></tr>
<tr><td>Short circuit current (I_{sc})</td><td>A</td><td>10.09</td><td>10.27</td><td>11.58</td><td>11.15</td><td>11.30</td><td>13.50</td><td>13.87</td><td>11.36</td></tr>
<tr><td>Module efficiency</td><td>%</td><td>19.2</td><td>19.7</td><td>20.2</td><td>20.7</td><td>21.4</td><td>21.5</td><td>22.1</td><td>20.9</td></tr>
<tr><td>Maximum system voltage (V_{DC})</td><td>V</td><td colspan="8">1000</td></tr>
<tr><td>Series fuse rating</td><td>A</td><td colspan="8">20</td></tr>
<tr><td>Power Tolerance</td><td>Wp</td><td colspan="8">0/+10</td></tr>
<tr><td colspan="10">Temperature ratings</td></tr>
<tr><td>Temperature Coefficient I_{sc}</td><td>%/C</td><td colspan="2">0.03</td><td colspan="3">0.064</td><td colspan="2">0.04</td><td>0.064</td></tr>
<tr><td>Temperature Coefficient V_{oc}</td><td>%/C</td><td colspan="2">-0.3</td><td colspan="3">-0.28</td><td colspan="2">-0.24</td><td>-0.28</td></tr>
<tr><td>Temperature Coefficient P_{max}</td><td>%/C</td><td colspan="2">-0.38</td><td colspan="3">-0.36</td><td colspan="2">-0.29</td><td>-0.36</td></tr>
<tr><td>NOCT (± 2°C)</td><td>°C</td><td colspan="2">44</td><td colspan="6">16,8</td></tr>
<tr><td>Operating temperature</td><td>°C</td><td colspan="8">-40/+85</td></tr>
<tr><td colspan="10">Mechanical properties / Components</td></tr>
<tr><td>Module weight</td><td>kg</td><td colspan="2">21.5</td><td colspan="2">21.3</td><td>20.8</td><td colspan="2">21</td><td>25.8</td></tr>
<tr><td>Dimensions (H / L / D)</td><td>mm</td><td colspan="2">1992/994/38</td><td colspan="2">1914/1036/35</td><td>1864/1029/35</td><td colspan="2">1721/1133/35</td><td>2263/1037/35</td></tr>
</table>

B.2.2 Kness Energy

Table B.9 – Kness Energy series SNRG-FR72-MONOPERC-SBB 370 to 390 *W*

Parameter \ Type		SNRG·FR72-MONOPERC -SBB370 Вт	SNRG·FRn-MONOPERC-5BB375 Вт	SNRG·FR72-MONOPERC-SBB380 Вт	SNRG·FR72-MONOPERC-5BB385 Вт	SNRG·FR72-MONOPERC-5BB390 Вт
Electrical specifications						
Module Power (P_{max})	*Wp*	370	375	380	385	390
Maximum power voltage (V_{pmax})	*V*	40.1	40.3	40.6	40.8	41.0
Maximum power current (I_{pmax})	*A*	9.23	9.31	9.39	9.47	9.55
Open circuit voltage (V_{oc})	*V*	48.6	48.8	49.0	49.2	49.4
Short circuit current (I_{sc})	*A*	9.72	9.79	9.86	9.93	10.0
Module efficiency	*%*	19.1	19.4	19.6	19.9	20.1
Maximum system voltage (V_{DC})	*V*	1000				
Series fuse rating	*A*	15				
Power Tolerance	*Wp*	0/+4.99				
Temperature ratings						
Temperature Coefficient I_{sc}	*%/C*	+0.07				
Temperature Coefficient V_{oc}	*%/C*	-0.36				
Temperature Coefficient P_{max}	*%/C*	-0.38				
NOCT (± 3%)	*°C*	20				
Operating temperature	*°C*	-40/+85 *°C*				
Mechanical properties / Components						
Module weight	*kg*	21.1				
Dimensions (*H* / *L* / *D*)	*mm*	1956 / 992 / 35				

Table B.10 – Kness Energy series MWT Mono PERC Half-Cut Module 445 to 465 *W*

Parameter \ Type		SPP445NHJH	SPP450NHJH	SPP455NHJH	SPP460NHJH	SPP465NHJH
Electrical specifications						
Module Power (P_{max})	*Wp*	445	450	455	460	465
Maximum power voltage (V_{pmax})	*V*	43.6	43.8	44.0	44.2	44.4
Maximum power current (I_{pmax})	*A*	10.22	10.28	10.35	10.42	10.48
Open circuit voltage (V_{oc})	*V*	52.7	52.9	53.1	53.3	53.5
Short circuit current (I_{sc})	*A*	10.75	10.82	10.89	10.95	11.0
Module efficiency	*%*	20.1	20.3	20.5	20.8	21.0
Maximum system voltage (V_{DC})	*V*	1500				
Series fuse rating	*A*	15				
Power Tolerance	*Wp*					
Temperature ratings						
Temperature Coefficient I_{sc}	*%/C*	0.06				
Temperature Coefficient V_{oc}	*%/C*	-0.28				
Temperature Coefficient P_{max}	*%/C*	-0.36				
NOCT (± 2°*C*)	*°C*	43				
Operating temperature	*°C*	-40/+85 *°C*				
Mechanical properties / Components						
Module weight	*kg*	26				
Dimensions (*H* / *L* / *D*)	*mm*	2005 / 1105 / 35				

Навчальне видання

ІВАХНОВ Андрій Віталійович
КУЛАПІН Олександр Валентинович
МАХОТІЛО Костянтин Володимирович
БУЛГАКОВ Олексій Віталійович
ГРИЦЕНКО Владислав Віталійович
ШОКАРЬОВ Дмитро Анатолійович

ПРОЄКТУВАННЯ ФОТОВОЛЬТАЇЧНИХ ЕЛЕКТРИЧНИХ СТАНЦІЙ

Навчальний посібник
для студентів спеціальності
141 «Електроенергетика, електротехніка та електромеханіка»
Англійською мовою

Відповідальний за випуск проф. Лазуренко О. П.

Роботу до видання рекомендував проф. Любарський Б. Г.

В авторській редакції

План 2024 р., поз. 131

Підп. до друку 29.11.2024 р.
Гарнітура Time New Roman
Ум. друк. арк. 14,8.

Видавничий центр НТУ «ХПІ»,
Свідоцтво про державну реєстрацію ДК № 5478 від 21.08.2017 р.
61002, Харків, вул. Кирпичова, 2.

Електронне видання