

POLITECNICO DI TORINO

Master Degree

Energy and Nuclear Engineering

Master Thesis

**Optimization of PV generator/inverter
coupling in terms of DC cable losses and
series/parallel connections of PV modules**



Supervisors:

Prof. Filippo Spertino

Prof. Oriol Gomis Bellmunt (UPC)

Candidate:

Andrea Orlandini

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Abstract

The PV system has already a fundamental role in the energy market. Therefore, this kind of plant still grows in terms of sizing and also the research about new technology is always a very current topic. For these reasons, the study on the photovoltaic systems can include different matters starting from the better modelling of one specific physical effects arriving at financial analysis in order to help an investor in their choices. Usually, to address in these choices, experts and engineers use a simulation software able to replace the conditions of one site and make a comparison with another one in a more accurate way. The present thesis has the scope of implementing an open source program developed on MATLAB software, in order to create an accurate simulation. The MATLAB program was written in collaboration with the Universitat Politècnica de Catalunya (UPC) in Barcelona. The program starts with the weather data's inputs of the location and simulates the hourly energy production of PV plant in the entire year. The main focus of the thesis's work is the implementation of the DC cable losses model and its effect in terms of technical and economic points of view. In order to create a model of the specific plant layout, the algorithm is explained in detail with all components that participate in the cabling connection. In the case study is considered a PV plant with a size of 1 MW and a central inverter configuration in different locations. In addition, the financial model compares the investment cost of DC cables with the cost of all energy lost. It shows how the best configuration of the cabling layout is obtained with a fixed maximum voltage drop limit between 1% and 1.5% of the operational V_{dc} of the plant depends on the location. In conclusion, the advantage of MATLAB code is its flexibility; it could be implemented by adding other specific models in order to study a specific problem presents in the PV plants.

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Abbreviations

EPIA = European Photovoltaic Interest Organization

CAGR = Compound Annual Growth Rate

LCOE = Levelized Cost Of Energy

RES = Renewable Energy Source

IRENA = International Renewable Energy agency

GHG = Greenhouse Gases

CIGS = Copper Indium Gallium (di)Selenide

CdTe = Cadmium Telluride

PV = Photovoltaic

DC= Direct Current

AC=Alternating Current

MPPT=Maximum Power Point Tracking

GHI =Global Horizontal Irradiance

DHI=Diffuse Horizontal Irradiance

BHI=Beam Horizontal Irradiance

DNI=Direct Normal Irradiance

POA=Plane Of Array

G=Irradiance (W/m²)

SB = String combiner Box

AOI= Angle Of Incidence

SAM =System Advisor Model

GME = Gestore Mercati Elettrici

OIME = Operador del Mercado Ibérico de Energía

LCA = Life Cycle Assessment

1 Introduction

1.1 Background

Renewable energy, with photovoltaic in a leading role, needs to provide an increasing share of the world's energy demand in order to decrease the emission of greenhouse gases produced by our global society. In operation, photovoltaic plants generate electricity without emission of any kind. Comparing one kWh produced by PV plants and one kWh generated by fossil fuel the first option is the most sustainable.

The photovoltaic industry has understood that the advantages gained using renewable energy should be emphasized with a responsible management of environmental, health and safety aspects.

According to a report that predicts the future global market, published by European Photovoltaic Interest Organization (EPIA), the PV industry represents a growing market. With the decreasing of PV costs, PV applications will become competitive in more situation such as public and private transportation [1].

1.2 Objective

This thesis has the goal to develop a model using MATLAB software, which is able to simulate accurately the cable losses in the DC side of a solar photovoltaic plant and their impact on the entire power production of PV plant. The model starts from a previous MATLAB program, which simulates the production of solar photovoltaic plant through the value of global horizontal irradiation (GHI) until the I-V curve of a single module.

1.3 Motivation

The purpose of this project is to develop an implementation of a PV model based on MATLAB and, considering a specific layout of the photovoltaic plant, calculate the cable losses and consequentially the operation conditions of the inverter. After that, an economic analysis is implemented in order to understand the optimum design of cable sizes, with a trade-off between initial investment cost for the cables and energy loss in the entire life of the plant.

Among the different renewable technologies, this project focuses on solar PV plants because it has an enormous potential to become a fundamental player in the future energy mix. The future trends consist to design large size power plants, and this make the specific topic of cable losses an important problem for PV large plant.

1.4 Structure

The structure of this thesis can be explained as follow:

Chapter 1: this first chapter describes the thesis statement, the motivational background and the aim of the thesis's work.

Chapter 2: general description of a photovoltaic scenario and the diffusion of the technology in worldwide and the importance of shifting to cleaner energy. Another section concerns on the main components present in a large PV power plant and their functions.

Chapter 3: in this part is presented a recap of the fundamental concepts useful for the design of PV plant; in particular, are explained the definitions of different components of solar irradiance, the source weather data, the solar angles and the main guidelines needed to design a PV plant.

Chapter 4: this section describes the models of this project implemented on MATLAB with a briefly review of the previous work and its model. Every implemented model is described accurately with its sub-model and all equations, algorithms and assumptions.

Chapter 5: here is presented an introduction of the case study, the choice of every component in the plant and its topology. Then, are estimated the results and methodology calculation with a comparison between different location.

Chapter 6: in this chapter are briefly described the environmental impact of the developing PV plant.

Chapter 7: Conclusions of the thesis' work with some tips for a possible further analysis in order to implement the project

2 General view of PV technology

2.1 PV market global scenario

Photovoltaic system has an important part in the energy mix of several countries and it is a fast growing market.

From a global perspective, the PV market had a rapid growth in the last years: the global PV installed capacity grew from 23 GW in 2009 to 402 GW in 2017 [1] which is clearly visible in the Figure 2.1. The Compound Annual Growth Rate (CAGR) of PV installations was 24% between year 2010 to 2017 [2].

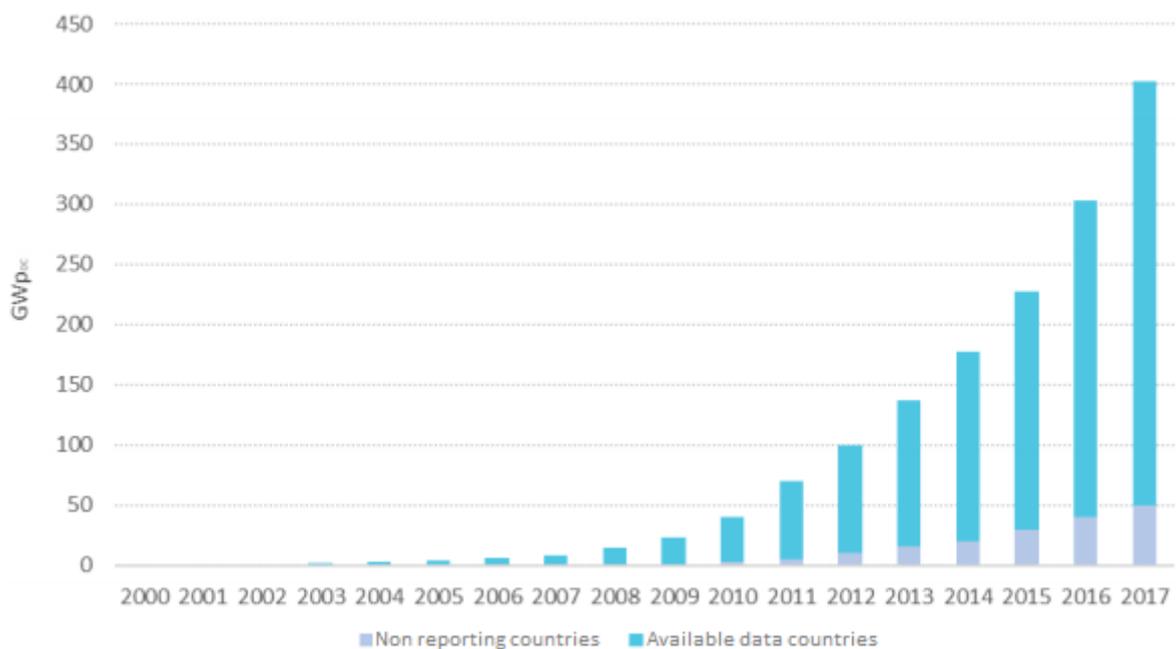


Figure 2.1: Evolution of total installed capacity (DC) [1]

The significant increase of market, during 2016, was mainly caused by China, where new installations were up more than 50 % of the country capacity of previous year, and India where its market is doubled in the same year.

In 2017, Europe’s contribution to the total cumulative PV installations amounted to 28% (compared to 33% in 2016). In contrast, installations in China accounted for 32% (compared to 26% in 2016) [2]. The latest data show the important role that the China will play in the next years. Therefore, the leaders of solar PV capacity per inhabitant are Germany, Japan, Belgium, Italy and Australia.

The Figure 2.2 shows the countries with higher PV additions in 2017. This graph can be useful in order to understand who will play an important role during the next years.

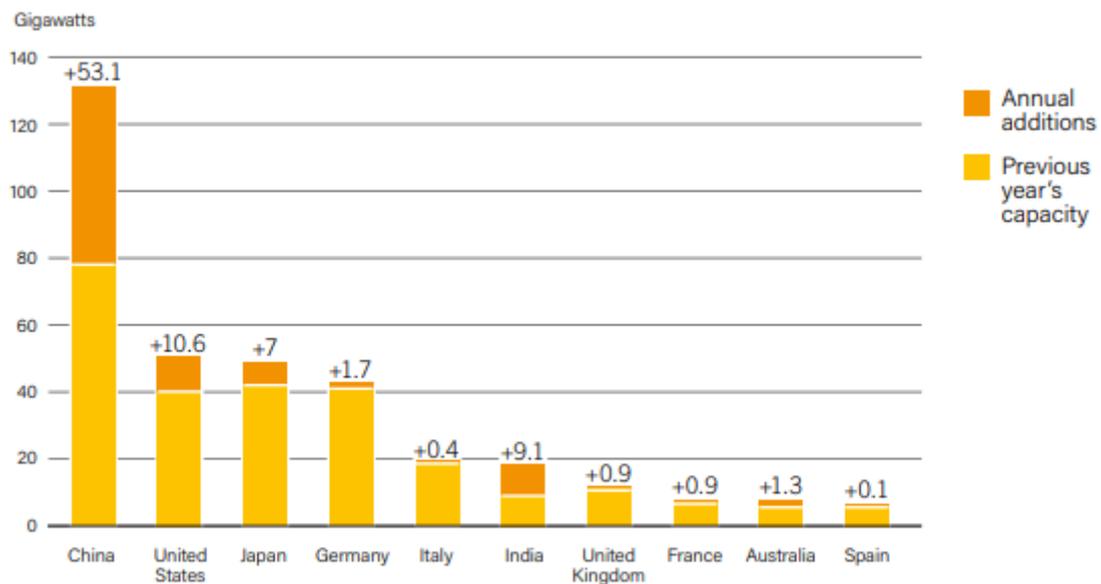


Figure 2.2: Top 10 Countries for Solar PV Capacity and Additions at 2017

The main reasons for this rapid growth of PV market can be caused by two drivers. The first reason is that the policies for the reduction of greenhouse gases emissions have a major role and are now present in almost all countries all around the world. For example, Europe stipulated a 20-20-20 accord [3] where one of targets is the reduction of 20% of CO₂ emissions within 2020 and the PV plants helps to reach this target for the electrical production. Another example for reduction of GHG’s emissions is the one made by the political behaviour in Italy. Thanks to subsidies and policy for a profitable Feed-in Tariff, the PV market of the country grew rapidly during the years of the policy that was available from 2005 to 2013. This policy has increase the electricity generated by PV in the country, that remains remarkably high, with 8.2% of the energy needs coming from PV in 2016 [4].

The second reason of this growth is the decreasing of the PV technologies price especially for the PV modules thanks to a large adoption of this technology. Another good indicator to compare several renewable power technologies is the Levelled Cost Of Energy. This parameter is an important indicator for the comparison of power plants because it is independent from the kind of technology used. LCOE represents the costs of producing one unit of energy (kWh) considering the whole lifetime. It can be useful for the calculation of the minimum price at which energy should be sold to reach a specific return of investment.

2.2 Main components of PV plant

In this section of the work are described the main components used a large-scale PV solar power plant. This section presents just a recap of the mainly components of PV power plant because a detailed analysis of every component is not part of the scope of this work.

Regardless of configuration and capacity, operation of any PV installation requires such key components as photovoltaic solar modules, their mounting system, String Combiner Boxes, inverters and DC cables.

A simplified diagram of a grid-connected PV system can be found in the figure 2.1.

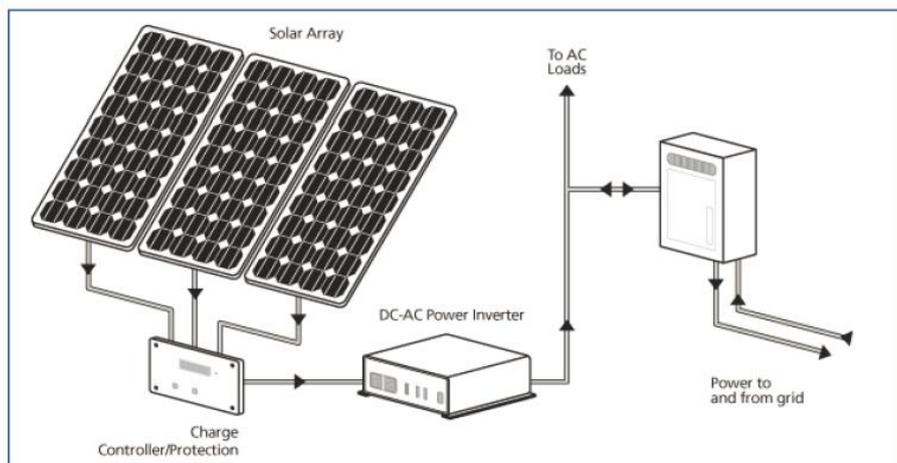


Figure 2.1: Grid connected PV system

2.2.1 PV module

There are different types of PV modules technologies depending on the kind of material that is used and the manufacturing process of the cell.

The PV cells can be classified in three classes:

- First generation: these cells are made in Silicon. This class of cells is the most common because it is cheaper and well-know. The main characteristics are the high quality of materials (single-junction), high energetic cost of manufacturing process and an efficiency around 15-18 % [5]
- Second generation: thin film. The thickness of these cells is in the order of 1 μm . The cost of production in terms of energy and cost of this technology is very low but also the efficiency that is around 10-13 % [5]. The common material for this technology are Cadmium Tellurium (CdTe) and Copper Indium Gallium Selenide (CIGS)
- Third generation: Concerning on the new technology still being tested like as multi-junction cells able to absorbs the radiation in a large wavelength spectrum.

Therefore, the most used technology is the one made from Silicon, which is also the one used in this project.

Silicon is one of the most common elements in Earth, it has to undergo rigorous processes in order to obtain desired semi-conductor characteristics and be used as a photovoltaic final product. Depending of the manufacturing process, there are different kinds of silicon crystalline structures; monocrystalline photovoltaic cells, polycrystalline PV cells and back-contact ones.

The monocrystalline cell is the most expensive due to its higher purity of Silicon (99.99 %). This technology was the most used in the early years of PV applications. Multi-crystalline solar cells, or also called poly-crystalline (or Poly-Si) solar cells, are the result of trying to reduce the costs of production of Mono-Si cells by means of new crystallization techniques.

The voltage produced by one PV cell alone is not enough for common applications. By connecting several solar cells in series, the terminal voltage is multiplied by the number

of cells (N_c) that are connected in series. Due to the series connection, the total current remains the same of the one produced by just one solar cell.

All modules are created using the same elements, presented on Figure 2.3. The n-type and p-type semiconductors are simply plates made of silicon. The n-type plate is treated with Phosphorous, which create an excess of electrons. The p-type is treated with Boron, and become deprived of electrons. Putting together, the two Silicon plates create an electromagnetic potential which allows a DC current to flow between semiconductor plates.

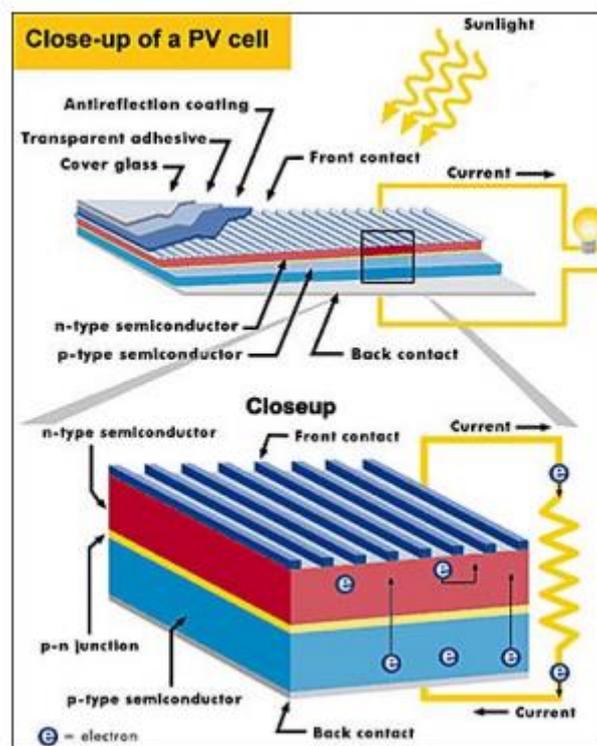


Figure 2.3: PV cell composition

Overall, the Mono-crystalline or m-Si modules, have the highest conversion efficiency than all commercial solar panels, in the range of 15-20% while polycrystalline modules operate in the range of 14-18% efficiency [5].

2.2.2 Inverter

The inverter is a fundamental component of any solar photovoltaic system, since it is the device that converts the normal DC output power of solar modules to an AC supply which can be injected into the grid. There are three different types of inverters, depending on the way in which they are integrated into the PV plant:

- String inverters: this typology of inverters derives from the way in which the modules are connected. In order to increase the voltage of the plant, the modules are connected in series and create a string that enters into the inverter with the same current. The main advantages are the easiest maintenance and management of module's failure, at the contrary, if there is a fault of only one module, the entire string will suffer in terms of energy production performance. The connection from string to inverter is presented in Figure 2.4.

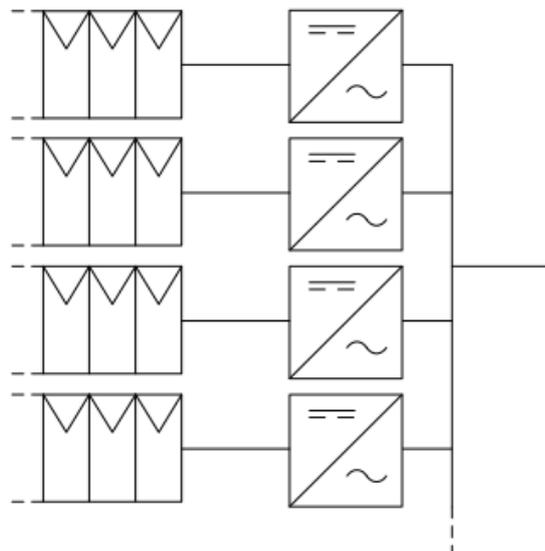


Figure 2.4: String inverter scheme

- Micro-inverters: it is a most recent technology and it works in the opposite behaviour respect the string inverter. In this inverter type there is a DC-AC converter on each PV module, and it is directly connected to AC circuit as shown in Figure 2.5. This means that for each panel there is one independent MPPT in order to follow the best Maximum Power Point as the consequence of a best

performance in terms of energy production. It is possible to understand that this technology is the most expensive also for the maintenance costs due to its complexity and to control the large number of components.

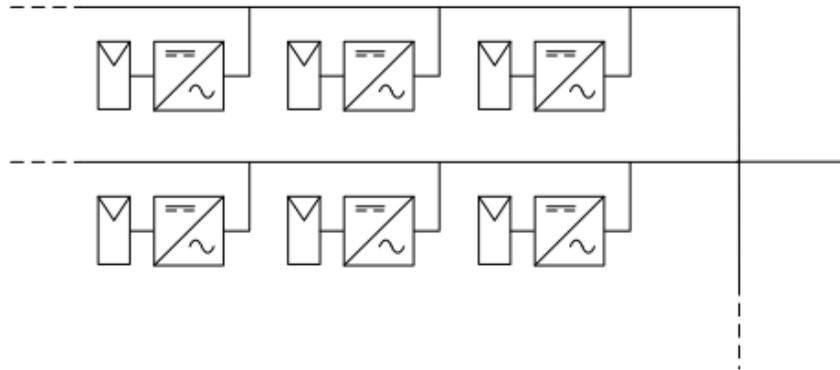


Figure 2.5: micro inverter scheme

- Central inverters: the common trend for a large size PV plant is to use this kind of inverters called “central array inverter”. Their working principle is very similar to the string inverters but they are cheaper and the layout is more easy to manage thanks to the low amount of the components. In this case the strings are connected in parallel with the same String Combiner Box, after that only one cable exits from the String Box to the inverter in which flow the sum of all currents’ string.

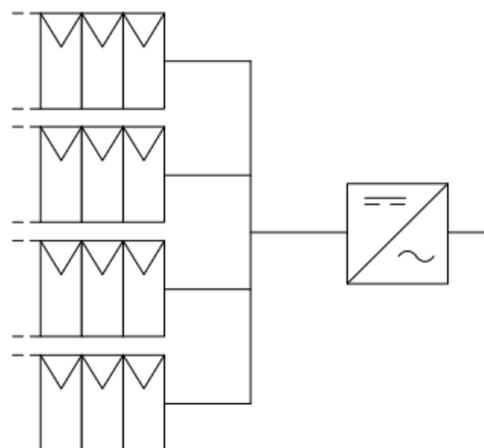


Figure 2.6: Central inverter scheme

In this work is presented a power plant with a large size, so it is used only one central inverter working with a configuration described in Figure 2.6.

The main characteristics for each PV inverter topology are resumed in the Figure 2.7 with a qualitative impact level on the plant. The letters used have the meaning of: L=low; M=medium; H=high.

		Central	String	Module integrated
General characteristics	Reliability	L	H	H-H
	Robustness	H	L	L-L
	Flexibility	L	H	H-H
	MPPT efficiency	L	H	H-H
Power losses	Mismatching	H	L	L-L
	Switching	H	L	L-L
	ac power losses	L	M	H
	dc power losses	H	L	L-L
Power quality	ac voltage variation	L	H	H-H
	dc voltage variation	H-H	M	L-L
	voltage balance	H	M	L
Cost	Installation cost	M	H	H-H
	dc cables	H	L	L-L
	ac cables	H	M	H
	Maintenance	L	M	H-H

Figure 2.7: Comparison between different inverter topologies [6]

2.2.3 String Combiner Box

In a large power plant with a central inverter, the connection of modules' strings in parallel is made into a String Combiner Box. The main function of this device is the capability to connect a larger number of strings in parallel and to control their principal operating parameters using some sensors. The SB has a protection function against weathering and to protect the circuit from overcurrent through fuses. Many String Boxes have other functions in order to control the parameter of the photovoltaic plant:

- Control of voltage and current of each strings
- Operational state of the fuses

- Temperature control inside the boxes
- Possibility to control all parameters directly on module for maintenance
- DC switch in order to separate the string group at high voltage.

The maximum number of string depends on the amount of the clips in the input channels of String Box. This number can be easily customized by the manufacturing house. In Figure 2.8 is shown a String Combiner Box.



Figure 2.8: String Combiner Box with 6 channels

2.2.3 DC and AC cables

DC cables connect the PV modules between them and the inverters while AC cables connect the rest of electrical equipment inside the PV plant. The cables installed in a solar plant should meet the international and local requirements of these type of installations.

This work focuses the attention on the losses in the DC cables. There are three main parameters defining the selection criteria for DC cables:

- Cable voltage rating; the cable selected must supports the voltage of PV string of modules of PV plants. For this calculation open circuit voltage of PV modules is used.

- Current carrying capacity of the cable; the cable can be designed in order to supports the possible worst current in the electric circuit equal to short circuit current.
- Minimization of voltage drop; it is more important to reduce the voltage drop in the cables, an acceptable voltage drop value would be at most 3% but 1% or less cable loss can be achieved.

The cables installed in a specific PV solar plant must be adequately protected for the climate conditions of the site like as sunrays, moisture, rain and so on.

The solar cable used for PV plant can be made by a conductor of Copper or Aluminium and its cross section view is shown in Figure 2.9.

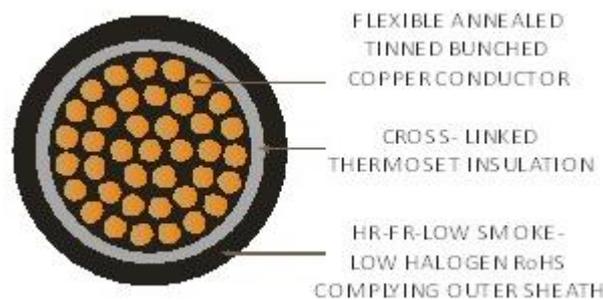


Figure 2.9 Construction characteristics of solar cable [7]

All the proprieties of commercial cables, according to the standards, are shown in the characteristics schedule of manufacturing companies.

2.3 Design considerations

The performance and reliability of a PV system depends highly on the location where the plant is situated. Many factors are considered in the choosing of the site and its analysis.

1. Location: the position of the Sun and its paths. The peak hours and the amount of the maximum solar radiation depends on latitude and longitude of the site.

Therefore, the ambient temperature is considered for the calculation of the number of modules in series based on DC voltage compatibility.

2. Orientation(γ) and tilt (β): to be applied in a fixed tilt system. As the rule of thumb, the system should face through south with a tilt angle equal to latitude. Optimal orientation and tilt angle also depend on the ground, microclimate, surroundings and obstacles.
3. Shading: it includes near field shading and far shading or horizon but is very difficult to predict. Shading effect can be considered similar to a mismatch phenomenon. When one module in a string is affected by shading, the entire string carry the current produced by the weakest module. Potential shading loss can be decreased by adjusting such design variables as azimuth and tilt, panel orientation and row spacing.
4. Soiling: those losses refer to the lost in power caused by snow, dirt, dust and other particles that cover the surface of the PV module. Dust formation is mainly caused by local weather, agricultural activities and traffic. Soiling could create annual losses higher than 7 % but can be reduced by half with regular washing. Dust is a thin layer that covers the surface of the solar array, and the typical dust particles are less than 10 μm in diameter but this depends on the location and its environment [8].
5. Grid availability: assessment of the electrical infrastructure: electrical protectors, distance to facility switchgear to adjust losses and costs, utility metering requirements.
6. Environment: vegetation, soil type, security and safety of the plant, feasibility of ground trenching and the system accessibility for inspection and maintenance.

3 Theoretical background

In this chapter are briefly introduced a review of the basic concepts of irradiance components and the calculations for design PV plant.

3.1 Solar Radiation

In this section it is described an explanation about the components of Sun's radiation.

The extra-terrestrial irradiance is defined as the radiation that can be found outside Earth's atmosphere. This value is a function of the distance Sun-Earth, but the distance suffers the elliptic path around the Sun of the Earth, so it is not always the same. The irradiance in outer space is called "solar constant" and it has a value of 1361 [W/m²]. The intensity of extra-terrestrial irradiance on a plane normal to the radiation depends on the day of the year. This correlation is expressed in the Equation 3.1. [9].

$$I_0 = I_{SC} \left[1 + 0.033 \cos \left(\frac{360 \times n}{365} \right) \right] \quad (3.1)$$

Where I_{SC} is the solar constant and n the number of the day in the year. The following step consists in the calculation of the contribution of irradiance horizontal respect the Earth surface using the Formula 3.2:

$$I_{0h} = I_N \times \cos \theta_z \quad (3.2)$$

Where θ_z is the solar zenith angle that is further explained in detail in the next section.

During the radiation that passes through the Earth's atmosphere, there is an attenuation of radiation due to absorption and scattering of long wavelength Sun's radiation. Only a part of extra-terrestrial radiation reaches the terrestrial region; this part is called terrestrial radiation. Other important variables are the clearness indexes defined in the Equation 3.3:

$$K_T = \frac{GHI}{I_{0h}} \quad (3.3)$$

Where K_T is the clearness index and GHI is the Global Horizontal Irradiance expressed in $[W/m^2]$.

When the irradiance reaches the Earth's surface, it contains two components; the beam part in the same direction of Sun's beam, and the diffuse one from reflection and diffraction of the atmosphere, generally called Albedo radiation. These components are reported in the Figure 3.1.

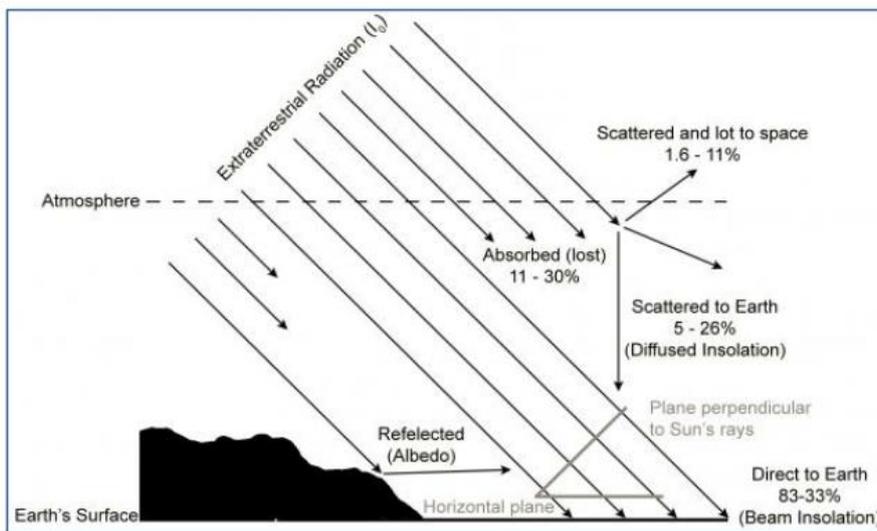


Figure 3.1: Solar radiation received by the Earth's surface [10]

The parts composing the solar radiation are related by some equations. The Global Horizontal Irradiance (GHI) is composed by the Beam Horizontal Irradiance (BHI) and the Diffuse Horizontal Irradiance (DHI) as explained in Equation 3.4.

$$GHI=BHI+DHI \quad (3.4)$$

Where BHI is the projection of Direct Normal Irradiance (DNI) on a horizontal surface:

$$BHI = DNI \times \cos \theta_z \quad (3.5)$$

As show in the Equation 3.5, Direct Normal Irradiance (DNI) is referred to a surface normal to the Sun rays.

In this work, it is always assumed that the Global Horizontal Irradiance, and eventually the diffuse one, are always known a priori from measured data.

3.2 Solar Angles and time shift

In order to calculate the angle of incidence (AOI) between the direction of the Sun's beams and the normal to the plane of the module some variables are required; the solar angles, equation of time and solar time.

3.2.1 Solar time

Firstly, it is important to understand the difference between solar time and clock time. The solar time is the time used for solar calculations and it is defined when the Sun reaches its highest point at noon. Sometimes the solar time can be more or less than 24 hours of clock time. Therefore, the clock time during 24 hours exactly every day, it is simply the time used in everyday life. This is a social issue in order to have a standard measure of life day with exactly the same time interval for each day.

The difference between the solar time and the clock time in hours can be expressed by the Equation 3.6:

$$t_s = t_{cl} - TZ + \frac{\psi_{loc}}{15^\circ} + EOT - DST \quad (3.6)$$

TZ represent the time zone of the location in hours, ψ_{loc} is the longitude of the location in degrees (East positive), EOT is the equation of time in hours and *DST* is the daylight-saving time in hours. The major difference between the two values is in the beginning of November when solar time is forward over 16 minutes respect clock time.

There are several reasons for these time differences. At first the orbit of the Earth is not a circle, but it is elliptical and the Earth moves faster when it is closer to the Sun due to gravitational issues. Secondly, there is an angle of obliquity of the Earth.

Mainly the sum of these two phenomena is the cause of the Equation Of Time described in the Figure 3.2.

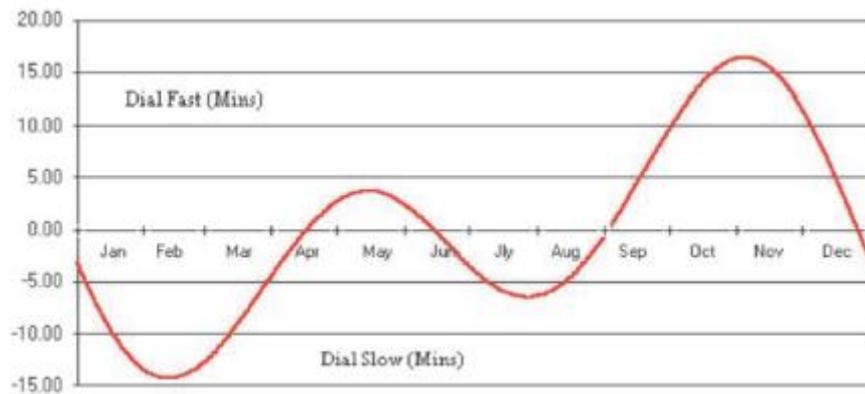


Figure 3.2: Equation of time (in minutes) for every day of the year

3.2.3 Hour angle

The hour angle represents the position of the Sun respect the meridian of the observer. It can be considering as the angular coordinate of the Sun if its position is projected on the plane of the equator. It is described in the Equation 3.7.

$$\omega = 15 \times (t_s - 12) \quad (3.7)$$

t_s is the solar time given by equation 3.6 and ω is the hour angle

At sunrise ω reaches the maximum value, after that it gradually reducing in function of time since the solar noon.

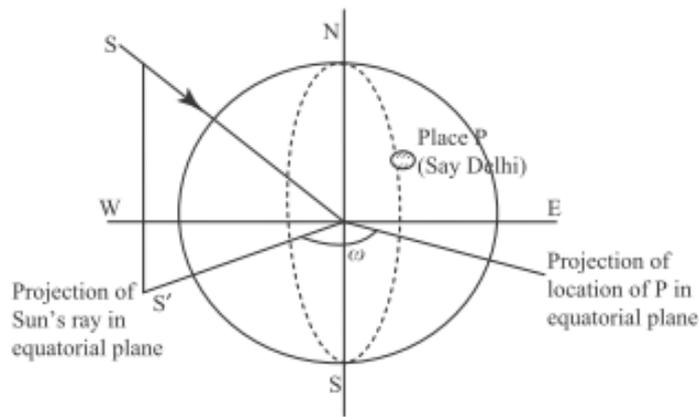


Figure 3.3 Hour angle

3.2.4 Solar Declination

The declination can be seen as the angle between the Sun's rays and the plane of the equator. Another definition can be the angle on which solar rays hits the Earth. The formula of the declination δ is the Cooper's empirical correlation explained in Equation 3.8:

$$\delta = 23.45 \sin \left[(284 + n) \times \frac{360}{365} \right] \quad (3.8)$$

The declination changes with the day of the year from approximately -23.4 degrees to +23.4 degrees at the winter and summer solstices respectively. The declination is also the main reasons why seasons exist.

3.2.5 Sun zenith and azimuth

Sun zenith and azimuth are two important values in order to locate the position of the Sun in the sky dome. The zenith is the angle between a vertical line and the direction of the Sun's beams and its complementary is the solar altitude. The azimuth is the angle between

the geographic South (different from magnetic one) and the projection of the Sun on a horizontal plane in the site.

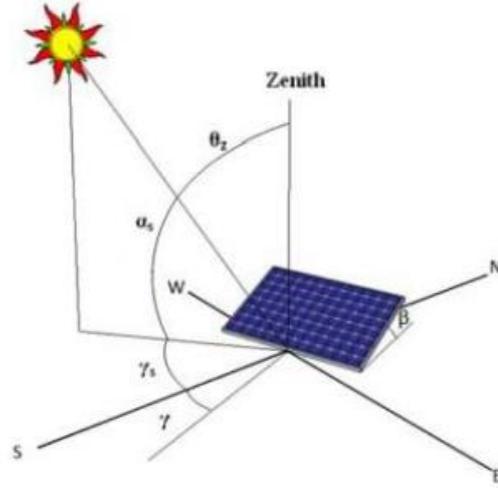


Figure 3.4: Solar zenith θ_z and solar azimuth γ_s .

By the figure, all the angles can be calculated with geometrical considerations. The θ_z is calculated from the Eq. 3.9 as:

$$\theta_z = \arccos(\cos\varphi\cos\delta\cos\omega + \sin\varphi\sin\delta) \quad (3.9)$$

And the solar altitude α_s is simply the complementary angle described by the Formula 3.10:

$$\alpha_s = \frac{\pi}{2} - \theta_z \quad (3.10)$$

At the end, the Eq. 3.11 estimates the solar azimuth γ_s .

$$\gamma_s = \sin\omega \left| \arccos\left(\frac{\cos\theta_z\sin\varphi - \sin\delta}{\sin\theta_z\cos\varphi}\right) \right| \quad (3.11)$$

Where φ represents the latitude of the location in radians (positive in Northern hemisphere), δ and ω are respectively hour angle and declination discussed previously.

3.3 Weather data source

The importance of the quality of solar radiation data and its assessment in any kind of PV installation is indisputable because it significantly affects the expected output of the system. Solar radiation measurement data, either from a satellite or a ground station, is considered to be the most reliable source. However, annual average measurement campaign is not enough to predict accurate annual irradiance and potential production value. The studies have shown that the annual mean value can differ from long-term by 5-20 % (for GHI and DNI respectively). Hence, long-term data for solar irradiance is applied in order to estimate the variance of the production [11].

Nowadays many various meteorological databases, either in-built into a simulation tool or importable, are available. It is rather difficult to evaluate that database represents the real amount of radiation received by the surface since it is site-dependent parameter. Additionally, databases might have different input parameters, time steps, and spatial resolution of either measured or synthesized data. Measurement data can be obtained from a ground observation station or thanks to satellite.

Therefore, weather data might contain monthly or hourly data from terrestrial observations, satellites, or be synthetically generated. Datasets cover different areas and time periods with Global Horizontal Irradiance to be the one common parameter and ambient temperature as the second one.

4 Model of the PV plant

4.1 Previous work

In this section is explained a briefly description of the previous starting model used in the simulation. This section is important in order to understand the starting point of the work of this thesis and its assumptions made [12].

4.1.1 Model of plane of array irradiance

The plane of array irradiance is important because the panels that it is considered in the plant have a fixed tilt angle. Therefore, only a part of the irradiance reaching the cells and it depends on the Angle of Incidence between PV panel and Sun's rays. The Plane Of Array irradiance is composed by three components; POA beam irradiance, POA ground diffuse irradiance and POA sky diffuse one as explained in the Eq. 4.1:

$$E_g = E_b + E_{sd} + E_g \quad (4.1)$$

E_b represent the beam irradiance hits the POA; the calculation of this component does not need any assumption but only geometrical consideration described in Formula 4.2:

$$E_b = \text{DNI} \cos \theta_{AOI} \quad (4.2)$$

Where AOI is the Angle Of Irradiance and the DNI is the Direct Normal Irradiance previously explained.

For the Ground Diffuse Irradiance, it is considered the reflected part of terrestrial irradiance as an isotropic behaviour. So the only parameter needed is the view factor of the panel:

$$E_b = \text{GHI} * \rho \frac{1 - \cos\theta_t}{2} \quad (4.3)$$

Where θ_t is the tilt angle of the panel and ρ is the albedo factor. The albedo factor can vary from 0 to 1 depends on the portion of irradiance reflected by the ground. If there is not special ground like sand or snow, an albedo is equal to 0.2 in a good approximation [12].

For the analysis on POA of sky diffuse irradiance there is the assumption that the diffuse irradiance is composite only of two parts; one component is isotropic and other one is circumsolar aligned in direction with solar rays. The model developed by Hay-Liu is used for this project. The formula 4.4 is the same of PVsyst software [12]:

$$E_{sd} = \text{DHI} \left[k_b \cos(\theta_{AOI}) + (1 - k_b) + \left(\frac{1 - \cos\theta_t}{2} \right) \right] \quad (4.4)$$

Where:

- DHI is the diffuse horizontal irradiance;
- k_b is the beam clearness index discussed;
- θ_{AOI} is the angle of incidence of the Sun's rays;
- θ_t is the tilt angle of the module.

The first part of the Equation 4.4 is referred on the anisotropic part due to the diffuse irradiance, the second term represents an isotropic part and the last term is concerning the view factor between the sky and the PV panel.

There is also an incident angle modified model in order to consider the optical losses due to that part of irradiance reflected by the module's surface. The IAM, calculated by the Eq 4.5, described the ratio of the transmittance of the incidence's angle of module against the angle of incidence with the ground corresponding with $\text{AOI} = 0$.

$$IAM = 1 - b \left(\frac{1}{\cos \theta_{AOI}} - 1 \right) \quad (4.5)$$

Where b is a constant called fitting parameter (unitless). The IAM is different for each component of irradiance. A deeply explanation of the IAM's component's is presented on PVsyst manual [13].

At this point, the effective plane of array irradiance E_g can be calculated to estimate the real part of irradiance that hits the surface of the PV cells of the module. This parameter is the effective data for the input of I-V model on MATLAB software and it is calculated by the Equation 4.6:

$$E_g = SF(E_b IAM_b + E_{sd} IAM_{sd} + E_g IAM_g) \quad (4.6)$$

4.1.2 Model of the module I-V curve

This model is the most important because it generates the current-voltage curve of the chosen PV module and consequentially its power produced at working condition.

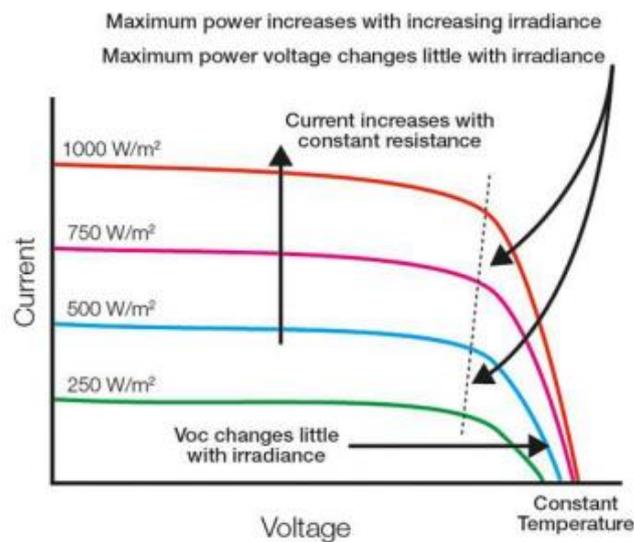


Figure 4.1: Effect of the Irradiance on the IV curve [14]

As shown in the Figure 4.1, the power generated by the PV module depends on its I-V characteristic curve, temperature and irradiance conditions. This model does not consider the mismatch losses so the maximum power point is always the working point of the module.

The model used to solve the I-V curve is the single diode model. In this model the cell is modelled like as current source (I_L) connected in parallel with a reverse diode with current (I_D). To model the resistance of the cell, there are two resistances; one connected in parallel called shunt resistance (R_{sh}) and the other one in series (R_s). In Figure 4.2 is presented an equivalent electric circuit of a single diode model.

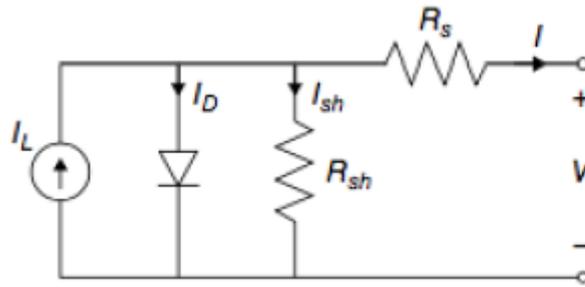


Figure 4.2: Equivalent electric circuit of single diode model

At fixed temperature and irradiance conditions, the equation 4.7 describes the current passes through the circuit:

$$I = I_L - I_0 \left[\exp\left(\frac{V + IR_s}{a}\right) - 1 \right] - \frac{V + IN_s R_s}{R_{sh}} \quad (4.7)$$

Where the I_0 is the diode saturation current in Amps, I_L is the photo-generated current also in Amps, V is the voltage of module, the constant a is the parameter function of diode defined in the Equation 4.8, R_s and R_{sh} are respectively the series and the shunt resistance of the cell and N_s represents the amount of cells in a row of the PV module.

$$a = \frac{nkT_c N_s}{q} \quad (4.8)$$

Where n is the diode ideality factor (often called γ), k is the Boltzmann's constant, q is the electron charge, and the temperature of the cell T_c .

In the Equation 4.7 the second term is multiplied by I_0 represents the current flowing in the diode while the third term represents the current flowing in the shunt resistance. The formula is an implicit non-linear equation and the solution for any values of temperatures and irradiances is not trivial.

Firstly, to solve the equivalent circuit of single diode model expressed from Eq. 4.7 is necessary to calculate five parameters; I_L , I_0 , n , R_s , and R_{sh} at reference conditions ($T=25^\circ\text{C}$; $G=1000 \text{ W/m}^2$). After that the same variables are recalculated for other values of T and G . Usually, from the PV module datasheet are known 5 characteristics:

- V_{OC} = Voltage open circuit condition
- I_{SC} = Short circuit current
- I_{mpp} = current at maximum power point
- V_{mpp} = voltage at maximum power point
- μ_{SC} = coefficient of the short circuit current

Therefore, in order to calculate the previously parameters five equations are needed. The first 3 equations are writing from the three known points setting the conditions; I_{mpp} and V_{mpp} in the maximum power point and open circuit voltage condition. The other two equations are concerning on the derivative of the V_{OC} equal to the open circuit voltage and the derivative of the IV curve equals to zero in its maximum point (MPP). The accurate description of this part is referred on the previous work made in [12]. The explanation of the way to solve the system of 5 equations reducing the equations in three as the PVPsyst method is found in literature [15].

Solving the set of equations with a Newton numerical model and a proper initial guess the computational cost is limited and the program reaches the convergence very fast.

At this point, the equation is solved for any value of temperature and irradiance with a procedure explained in the work [12].

Once all the variables of the single diode model are given for any temperatures and irradiance conditions, it is possible to calculate all point of I-V curve and the maximum power point. The implicit equation must be solved setting a voltage vector from 0 to V_{oc} and generates the current vector. Then, the power vector is calculated multiplying the I and V vectors. The MPP is find with the MATLAB's maximum function for the power vector obtained. Using this algorithm, the accuracy of maximum power point is related to the lengths of the vector means the numbers of equally spaced points.

In this way the computational power is less than analytic method described in [15] but with a little cost in terms of accuracy.

There are some assumptions done in order to solve IV curve with this model. As mentioned before, the sset of equations is reduced to only 3 equations, this is possible thanks to the assumption or a measurement of four parameters; R_{sh} , $R_{sh_{exp}}$, R_{sh0} , γ .

Usually, the datasheet does not give all values that are needed, for this reason the same assumptions of PVsyst are used [13]. Otherwise, if the module is tested to measure the I-V curve at different conditions, there are different way to take out the parameters from the measured data. The first consist in an interpolation between the measure with different irradiance conditions to find reference parameters through a numerical optimization. The second one adding on the first method also the variation of temperature.

For resuming the step of IV model:

- 1) Once PV module is given, it is taken the I_{mpp} , V_{mpp} , I_{sc} , V_{oc} , μ_{sc} , (at reference conditions), N_s (number of cells in series), and A_c (cell area) from the datasheet.
- 2) If the parameters are for modelling the IV curve are available from database, skip the step 3)
- 3) R_{sh} and γ are guessed as previously explained, the reference parameters are calculated from set of 3 equations and after that the all 5 parameters are calculated for any temperatures and irradiance conditions.
- 4) The voltage vector is created and the current is estimated in each V value. The two arrays are multiply in order to obtain the power vector which represents the output DC power. The maximum of the power array is the MPP point.

The Figure 4.3 shows a typical I-V curve for a PV model and its DC power generated.

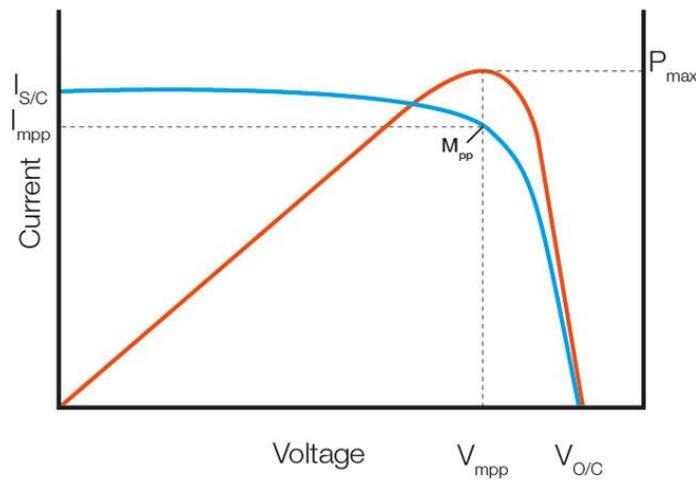


Figure 4.3 IV curve and DC power curve of PV module.

4.1.3 Model of Temperature of the cell

An important role in the correspondence between intensity and voltage is played by the temperature: its variation can modify the I-V curve. If the temperature increases the open circuit voltage decrease, with a consequence on the short circuit current that will increase; these variations will decrease the maximum power point. Because of these modifications it is possible to understand that if the irradiance is fixed, the temperature will increase, and the module's efficiency will decrease causing a lower power extraction. In the Figure 4.4 is possible to have a visual explanation of the effect of these variations.

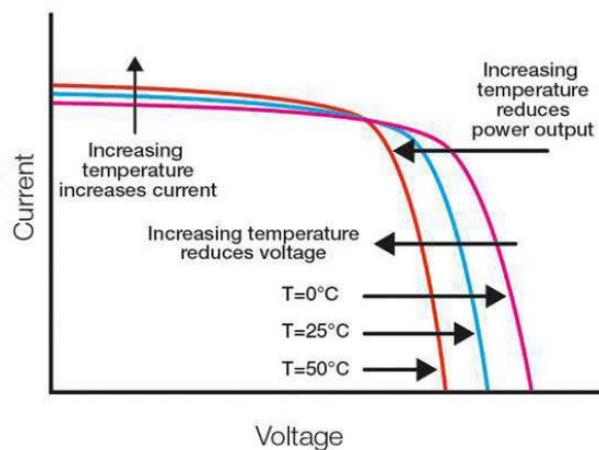


Figure 4.4 Temperature dependence of IV curve

It is possible to understand that the cells' temperature plays an important role; that's why there are a lot of different studies that focus the attention on this connection. The formulation of the method starting by the idea of an energy balance on the PV module: The incoming heat derives from the irradiance of the Sun and it is cooled thanks to the action of the ambient air for conduction and for convection given by the wind. Taking into account these actions, the temperature of the cell and its efficiency can be written as Eq. 4.11 and Eq. 4.13:

$$T_C = T_a + \frac{\alpha E_e (1 - \eta_m)}{U_0 + U_1 v_w} \quad (4.11)$$

$$\eta_m = \frac{P_{dc}}{E_e A_c} \quad (4.13)$$

Where:

- T_c represent the temperature of the module expressed in [$^{\circ}\text{C}$];
- T_a is the ambient temperature in [$^{\circ}\text{C}$];
- α is the adsorption coefficient;
- E_e is the POA effective global irradiance on the module in [W/m^2];
- η_m is the electrical efficiency of the module;
- U_0 is the constant heat transfer coefficient in [$\text{W}/^{\circ}\text{C m}^2$];
- U_1 represent the convective heat transfer coefficient in [$\text{W}/^{\circ}\text{C m}^2$];
- v_w is the wind velocity in [m/s];
- P_{dc} is the electric power in (W);
- A_c is the area occupied by the cells [m^2].

Supposing to know the ambient temperature measured every hour and the wind speed thanks to weather data, is possible to calculate the hourly POA. To reach these values the heat transfer coefficient and the adsorption coefficient are assumed as default number. The two equations are linked the one to the other, so was developed a numerical iterative algorithm to calculate the temperature hourly. The first step consists in guessing an initial value, then the temperature changes till the difference between the two steps reaches a

given value. The first value used, is calculated thanks to the Equation 4.11 fixing the T_c at the first hour of the morning equal to ambient temperature. To estimate the temperature of the following hours has been used the efficiency of the previous hour and then the old temperature is set equal to the guess temperature. For each hour has been searching a convergence reaching by steps:

- 1) The new DC power is calculated with the old temperature;
- 2) The efficiency is calculated inserting the new DC power in the second equation;
- 3) The new temperature is calculated inserting the new efficiency in the first equation;
- 4) The difference between the old and the new temperature is compared with a fixed value. If the value is higher, the simulation must run for a new cycle, if is lower it can be interrupted;
- 5) If the simulation has still to run, the old temperature is set equal to the new one.

All the fixed parameters are not easy to be calculated so, in absence of measured data, they are assumed equal to some default number. The adsorption coefficient α is set equal to 0,9; for what concern wind velocity. So, the authors of PVsyst [13] suggest setting U_v equal to zero and U_c equal to $29(\text{W}/\text{m}^2 \text{ K})$. It is important to remember that all the parameter used in the simulation can be modified, but if they are not changed the model will use the default values.

4.2 Model of the possible plant configuration

Once the IV curve is solved, the next step is the choice of the plant's layout assuming a given nominal power and a specific inverter. The required input data of this model are inverter's specific characteristics taken from the database elaborated by Go Solar California [16] and the PV module characteristics given by the database of Sandia National Laboratories [17].

The scope of this model is to calculate the total number of modules needed by the PV plant and their connection in terms of number of modules for each strings (N_s) and the number of strings in parallel (N_p). The modelling simulation does not consider the other

components from the DC/AC inverter to the electrical grid connection like as transformers and protection component for Medium and High Voltage.

For a general resume, it is important to remember that the current that flows in a string is equal to the current generated by one module while the voltage of a string is the sum of the voltage generated from entire number of modules that is composed the string.

Generally speaking, the voltage of the plant is represented by the number of modules in a string and the total current is defined by the number of strings of the plant.

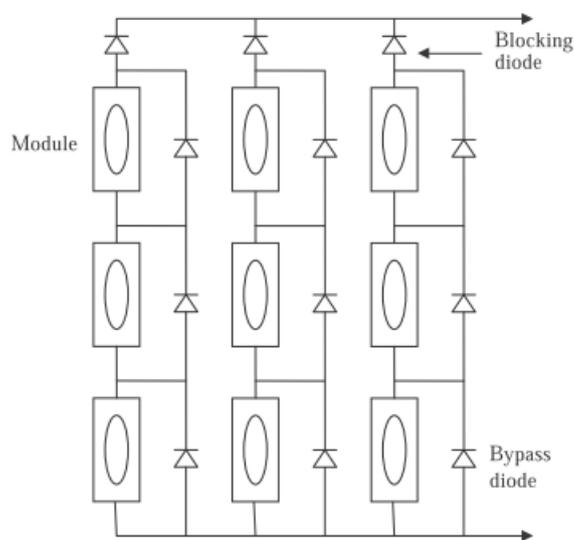


Figure 4.5 parallel and series connection of modules in the plant

In this thesis is studied the case of only one central inverter is connected to the all models of the entire plant. This configuration is a properly design for a small or medium size PV plants. Therefore, when the plant capacity is on the order of many Megawatts, it is suggested to use array inverters in order to reduce the power losses due to the DC cables and also to have a better monitoring of the plant parameter.

The choice of only one central inverter can be done for the easily management and control of the plant but also, for the better maintenance because there are only few components that can fail.

Once that the specific inverter is chosen, it has a range of operating voltages in which its Maximum Power Point Tracker works. In this way, the possible plant configurations depend on the voltage of the strings that must be inside the voltage range described by the Equations 4.14 and 4.15:

$$N_{S,min} = \frac{V_{min,MPPT}}{V_{mp}(T_{cell,max})} \quad (4.14)$$

$$N_{S,max} = \frac{V_{max,MPPT}}{V_{mp}(T_{cell,min})} \quad (4.15)$$

Where N_s is the number of module in series, $V_{max,MPPT}$ and $V_{min,MPPT}$ describes the range in which operates the MPPT of inverter. The V_{mp} is the voltage value corresponding to the maximum power point on the I-V curve where works the inverter in the extreme limits of cell temperature.

Another important limit is the maximum voltage supported by the inverter:

$$V_{string,OC,max} < V_{inv,input,max} \quad (4.16)$$

$$V_{string,OC,max} < V_{module,sys,max} \quad (4.17)$$

In order to respect the previous formula, it is necessary to calculate three values of voltage of photovoltaic modules; maximum, minimum and the maximum absolute open circuit voltage. This calculation can be done by the I-V curve model previously explained calculated for different temperature.

The V_{OC} voltage can be calculated with the minimum absolute temperature. The temperature in which the voltage values are given is defined by PVsyst manual:

- $T_{MAX,OPERATING} = 60 \text{ } ^\circ\text{C}$
- $T_{MIN,OPERATING} = 20 \text{ } ^\circ\text{C}$
- $T_{MIN,ABSOLUTE} = -10 \text{ } ^\circ\text{C}$

At this point, the model calculates all the limits described above and finds the range of a possible number of modules in series (N_s).

The chosen combination of plants layout takes the value N_s and calculates the number of strings N_p in order to reach the given power production on DC side grid. The value of P_{DC} is given from the datasheet.

$$N_p = \frac{P_{DC}}{P_{strings}} \quad (4.18)$$

To guarantee the safety of inverter is calculated a limit on the maximum current:

$$I_{string,max} \times N_p < I_{max,inverter} \quad (4.19)$$

The model gives in output a table with all different layouts for a specific inverter with additional specific parameters:

N_s	N_p	Vmin	Vmax	Pdc[kW]	Pac[kW]	# of modules
15	213	492	576	1022,9	997,51	3195
16	200	524,8	614,4	1024,5	999,07	3200
17	188	557,6	652,8	1023,2	997,82	3196

Table 4.1 Example of possible plant layout output

One of the possible configurations is chosen in order to create the final design of the plant.

The choice of the specific configuration is basing on two aspects:

- A higher voltage range causes a minor flow of current at the same DC power, it means a reduction of joule losses of the plant.
- Usually the maximum efficiency curve of inverter is close to the low values of voltage in which MPPT works, that means minor losses of inverter.

The two aspects explained are in contrast, the best configuration is a trade-off between these phenomena. Overall there is another aspect that has to be considered, the current of one strings depends on the module that had the badly performance (for any reason like shading, soiling, hotspots), so a lower number of modules per strings increase the reliability of the entire plant.

4.3 Model of DC cable losses

Usually the DC cable losses are calculating as a percentage around the 1-2% of the entire power production of the plant. The goal of this model is a detailed analysis about the sizing of different sections of the cables in order to calculate accurately the cable losses of PV plant.

The model is implemented for an application on a central inverter plant but it can be used also to study a plant with an array inverters connected. In order to optimize the topology of the plant layout and minimize its losses, a string combiner box is added between the strings of modules and the central inverter.

Usually, the String Combiner Box is used in medium and large size PV power plant. The main function of this component is to connect a set of parallel strings in the same components, the number of the strings attached depends on its manufacturing.

The insertion of String Boxes changes the parameters of the system.

From the following discussion, the N_p represents the number of strings attached on the same String Combine Box, N_{SB} is the number of String Boxes presents in the entire PV plant while N_s remains the same.

4.3.1 Model of string cable losses

To design the topology of the plant, a very important parameter is the distance between the strings in order to calculate the length of cables.

Therefore, for the calculation of the rows distance, the main issue that must be considered is the shading coming from the obstruction of Sun's rays from the front row on the row behind it. This is the only kind of shading considered in this work called self-shading effect. The visual explanation of this phenomena is shown in Figure 4.6.

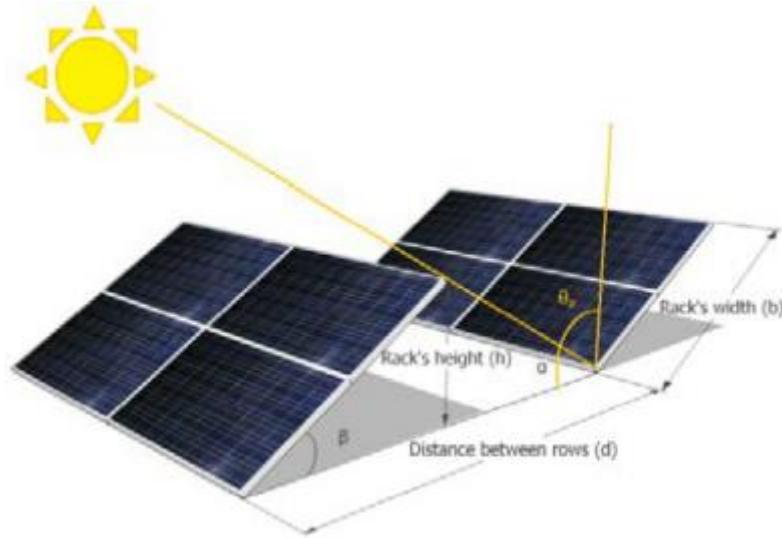


Figure 4.6 distance between rows of modules to avoid self-shading [18]

Therefore, the self-shading is impossible to avoid completely when the sun is at ground level, but it can be reduced. The better way to minimize this type of shading, as suggested in literature [18], is to consider the module remains shade free at least at the Winter solstice, the shorter day of the year in 21st on December. Assuming a flat ground, the “no shading distance” can be calculated as shown in equation 4.20:

$$d = b * \frac{\sin(90 - \beta + \theta_{z,21st Dec,12:00pm})}{\cos(\theta_{z,21st Dec,12:00pm})} \quad (4.20)$$

Where β is the tilt angle of the module and θ_z is the azimuth angle.

At this point, the surface occupation on the ground is available choosing a specific configuration in function of the PV plant size.

The electrical plant is mono phase so, for each string, two cables start from every string and go in the String Combiner Box.

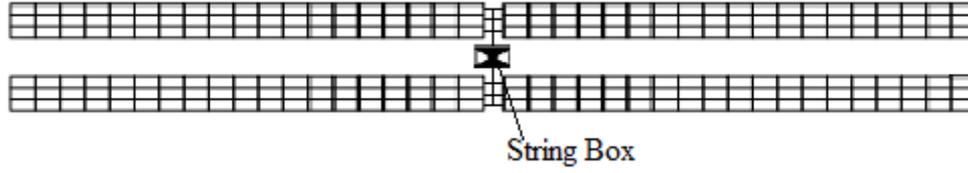


Figure 4.7: String Box connected to 12 strings

In order to simplify the approach, the String Box position is considered symmetric respect the strings, so the length of each string is assumed the same. The position of String Box is shown in figure 4.7.

For this work, it is supposed a tinned copper, but the choice could be modified in the model. Assuming the temperature of the cable equals to the cell temperature hourly, it is simpler to calculate the resistivity of copper shown in the equation 4.21:

$$\rho_{cu} = \rho_{cu,0}(1 + \alpha_{cu}(T_{cell} - T_{ref})) \quad (4.21)$$

Where:

- $\rho_{cu,0}$ = Copper resistivity at reference temperature [$\Omega \cdot \text{mm}^2/\text{m}$]
- α_{cu} = thermal coefficient [$1/^\circ\text{C}$]
- T_{ref} = reference temperature equal to 20 [$^\circ\text{C}$]

So:

$$R_{string} = \frac{\rho_{cu} * l_{string}}{S_1} \quad (4.22)$$

Where:

- R_{string} = string resistance [Ω]

- S_1 = cable section of the string [mm²]
- l_{string} = length of the string, function of N_s [m]

Therefore, with the approximation of same length for each strings, the current through each cable of the strings is the same. This hypothesis causes the same joule losses on each cable of row of modules and also same voltage drop. The assumption is called “no strings mismatch”.

$$V_{drop,string} = 2 * R_{string} * I_{module} \quad (4.23)$$

$$P_{loss,string} = 2 * R_{string} * I_{module}^2 \quad (4.24)$$

As mentioned before, the cables are bipolar so there are two cables for each string, this is the motivation of the factor 2 in the formulas 4.23 and 4.24. The current flows through the string is the hourly current generated by the IV curve of the module.

Overall, the losses until the String Boxes are shown in equation 4.25.

$$P_{before SB} = N_p * P_{loss,string,n} \quad (4.25)$$

Where N_p is the number of channels of the String Box means the number of strings attached on it.

4.3.2 Model of large section cables

A main part of this model is composed by the calculation of power lost and voltage drop for the cables coming from String Box to the central inverter. This part of analysis is the most important because the lengths that participate in the study is very large respect the string lengths.

In addition of the distance that minimizes the self-shading phenomena of the rows, another distance between the String Boxes is considered. For the walking of the

maintenance operator, another distance between sets of row is considered in the PV plant to make the ordinary checking operation or substituting electrical component (Eq. 4.26).

For the calculation of each cable lengths it is assumed also the minimal distance of the inverter from the first String (d_0). It is important to remember that the analysis is related only on the DC cables.

$$d_{SB} = n_r * d + D_p \quad (4.26)$$

Where n_r is the number of strings between the String Box, d is the distance of modules' rows previously explained and D_p is the distance of passage. All the variables are expressed in meters.

So the length of cable is strictly related on the topology of the plant as shown in Eq. 4.27:

$$\begin{aligned} l_{SB1} &= d_0 + d_{SB} \\ l_{SB2} &= d_0 + 2 \times d_{SB} \\ &\dots \\ l_{SBn} &= d_0 + n \times d_{SB} \end{aligned} \quad (4.27)$$

Where d_0 is the distance between the inverter and the nearest string on the cross direction respect strings.

At this time, the next step is the calculation of the cable resistance:

$$R_{SBn} = \frac{\rho_{cu} * l_{SBn}}{S_2} \quad (4.28)$$

Where S_2 is the section of the cable.

The consideration, as expected, is that the section of the cable from SB to inverter will be bigger than the section of the string because the amount of current that flows inside the

wires is higher and also the length cable. The current that flows can be calculate using the equation 4.29:

$$I_{SB} = N_p * I_{string} \quad (4.29)$$

As mentioned previously N_p is the number of channels of the String Box equal to the number of strings connected in parallel to the String Box.

Also the cable resistance is calculated for each SB cable and after that their voltage drop and their power loss are estimated as described in equation 4.24.

$$\begin{aligned} V_{drop,SB01} &= 2 * R_{SB01} * I_{SB}; P_{loss,SB01} = 2 * R_{SB01} * I_{SB}^2 \\ V_{drop,SB02} &= 2 * R_{SB02} * I_{SB}; P_{loss,SB02} = 2 * R_{SB02} * I_{SB}^2 \\ &\dots \\ V_{drop,SBn} &= 2 * R_{SBn} * I_{SB}; P_{loss,SBn} = 2 * R_{SBn} * I_{SB}^2 \end{aligned} \quad (4.30)$$

At the end, the total power losses and the total voltage drop for each line is calculated by summing the previous values with the results obtained before the String Box using equations 4.31 and 4.32.

$$P_{loss,n-line} = P_{loss,SBn} + N_C * P_{loss,string,i} \quad (4.31)$$

$$V_{drop,n-line} = V_{drop,SBn} + V_{drop,string} \quad (4.32)$$

At this point summing all contribution, the total power losses due to the cables is obtained as shown in equation 4.33:

$$P_{total\ loss} = \sum_{n=1}^{N_{SB}} P_{loss,n} \quad (4.33)$$

For the design plant with a central inverter as the assumption in this case, the length of cables had a critical role. The analysis of the cable voltage drops is very important because it affects the efficiency of inverter; and then the AC power production. In addition the MPPT of the inverter works only at one value of voltage input.

A large voltage drop difference between the line cables could provide a difference of current that cannot be neglected. This mismatch phenomenon between the cable line causes the operation of the modules in a point on IV curve different to Maximum Power Point with a negative consequence on power production. This phenomenon is deeply analysed in the next paragraph.

In order to avoid these problems, the cables have different sections proportionally to their distance from the inverter. The different sections produce almost the same voltage drop for all cables and reducing as much as possible the difference of voltage drops produced by the wires

For this reason a design parameter is the maximum possible voltage drop in the plant in order to avoid the significant differences of currents between the cables.

On the model implemented could be possible to set different values of maximum voltage drop in terms of percentage and to calculate the absolute voltage drop in order to have a different cable sizing for each voltage drop. The formula described the limit of voltage drop is calculated by Eq. 4.34

$$V_{max,drop} = \Delta V\%_{max} * V_{MPPT} \quad (4.34)$$

Where $\Delta V\%_{max}$ is one of the input values chosen in the design phase.

In order to compare the results for different maximum voltage drop limit, the simulation permits to create a voltage drop limit vector in order to have different values of $\Delta V\%$ that can be chosen in a smart way.

The V_{MPPT} in input on inverter is not a constant value, but it changes every hour and it depends on the weather and operational conditions of the PV plant. The assumption of this value is focusing on a value in which MPPT works for a higher number of hours.

The model calculates all cable's resistances and their voltage drops in order to maintain the values always minor than the drop limits fixed. The results of model are shown in Table 4.2 with all the possible configurations of cable sections relating to a maximum voltage drops in terms of percentage.

$\Delta V\%$	<i>line 1</i>	<i>line 2</i>	<i>line 3</i>	<i>line 4</i>	<i>line 5</i>
0,5	240	240	185	185	150
1	240	185	185	150	120
1,5	185	150	150	120	120
2	150	120	95	95	95
2,5	120	95	95	70	70

Table 4.2 Example of losses model's outputs

Once the fixed voltage drop is chosen, also the correlated cable resistances are fixed. Then, the model starts to run in order to build only one I-V curve representative the operating of the entire plant from the I-V curves of arrays.

4.4 Model of Array mismatch losses

For the work presented in this thesis all modules have the identical I-V characteristic so the mismatch due to their manufacturing is not consider. This section explained the procedure used in order to calculate the array mismatch between different current of wires that arrive to the central inverter.

The study of the currents' difference between the strings is important to validate the assumption made in this thesis' work. The assumption is that in each cable that reaches the inverter, flows the same current flows. This is not exactly true for the small difference between the cable's resistances due to the commercial size of the cable.

The model starts from I-V curve points of one module solved by the MATLAB program described in Section 4.1.2.

As mentioned on the Sections before, it is assumed a String Box component in which there are 12 strings of modules attached on it. The String Combiner Box is situated in a centric position and forms an array of twelve strings in parallel that have the same length of the cable.

Thanks to what explained before, it is possible to assume that there is not current mismatch between the strings on the same string box. The I-V curve of array is easily a scalar multiplication of the I-V curve of one module as described in Figure 4.8:

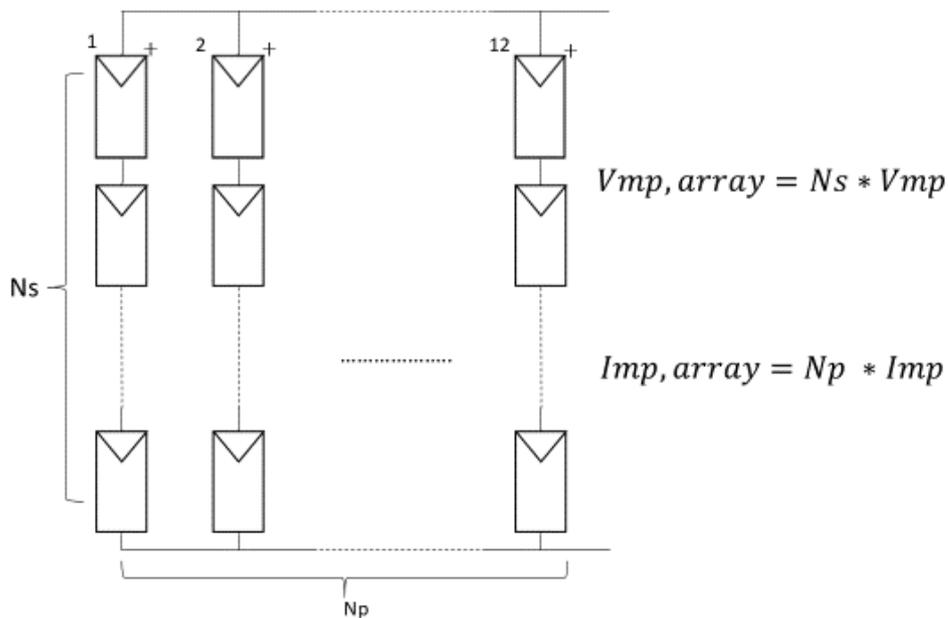


Figure 4.8: Layout of String Box array

Where I_{mp} and V_{mp} are the points of the maximum power on the I-V curve.

In the same way, the starting points of the x and y axis are respectively $V_{oc, array}$ and $I_{sc, array}$ that are calculated by the Eq. 4.35 and Eq 4.36.

$$I_{sc, array} = I_{sc} * N_p \quad (4.35)$$

$$V_{oc, array} = V_{oc} * N_s \quad (4.36)$$

It is important to remember that, the number of module in series of one string (N_s) represents a growth of voltage while the number of strings in parallel on the same string box (N_p) rises the current in the IV array's curve.

Therefore, the model calculates all points of IV curve of the SB's array with the equations described above.

The wires with a large section, that start from the SB to the inverter, have different cables' resistances due to their sections. This phenomenon causes different voltage drops that produce various currents downstream of the inverter that is the main point of this paragraph.

Then, the addition of the cables' resistances is estimated in terms of voltage drops, so the IV curve for each array is recalculated by the subtraction of the resistance's voltage drop on the operating point of array's IV curve (Eq 4.37) as Figure 4.9:

$$V_{, drop, array, n} = V_{, array} - I_{, array} * R_{, array, n} \quad (4.37)$$

Where $I_{, array} * R_{, array, n}$ represents the voltage drop related to the n-array.

The calculation on Eq. 4.37 is repeated for every array of String Box.

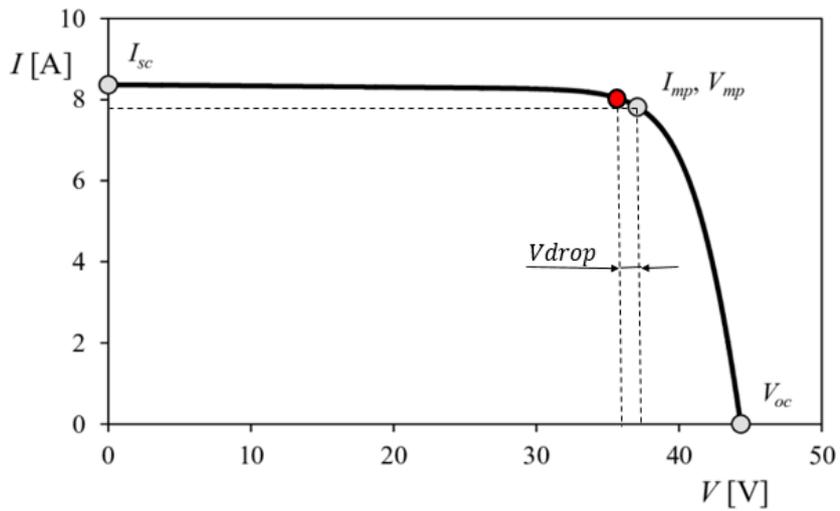


Figure 4.9: New operating point of array on IV curve

The inverter works with only one value of voltage, so in order to have the same voltage on every IV curves of arrays a linear interpolation is used. The function of MATLAB ‘interp1’ makes interpolation between all points for a specific array’s curve. It provides a new series of current points for the corresponding fixed voltage points.

As result of this process, every IV curve of array have the same points of Voltage curve but with different corresponding values of current. The Figure 4.10 shows the interpolation procedure for I-V equivalent curve of one String Box array in order to translate its current points on standardized voltage points.

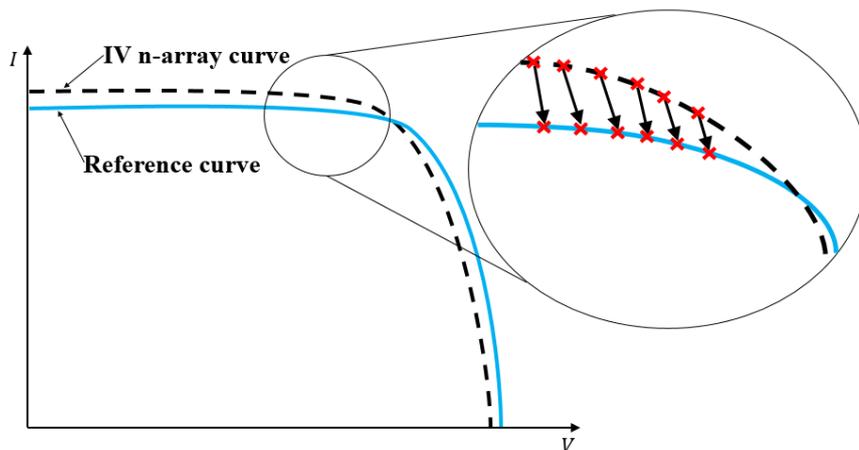


Figure 4.9: Interpolation of IV n-array points on reference V points.

Then, summing all currents of String Box arrays, the I-V equivalent curve for the entire plant is obtained. Consequentially, the Maximum Power Point in which operates the inverter is found.

The V_{mp} of inverter is used as reference in order to obtain the different currents that flow into each wire. At the end, the current mismatch between the wires and the related power losses are determined.

Overall the working process of algorithm for current mismatch analysis is resumed in the flow chart presents in the Figure 4.10:

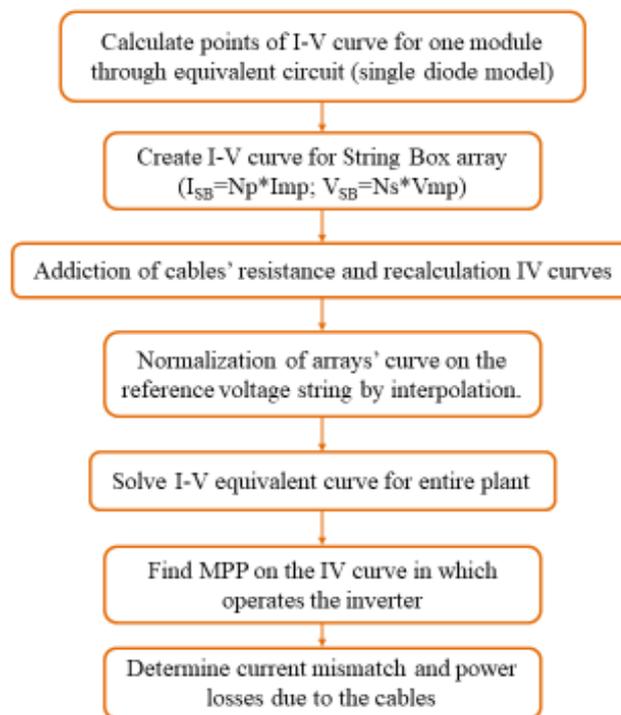


Figure 4.10: Flow Chart of mismatch model

4.5 Model of the inverter

In this model the scope is to create the efficiency curve of inverter and find the correlation between DC and AC power of the plant. The model is based on the algorithm designed

by SAM [18]. The model is based on empirical coefficient found by experimental parameters. Starting from the input data shown in equation 4.38:

$$P_{ac,out} = f(P_{dc,in}, V_{dc,in}) \quad (4.38)$$

The formula 4.38 is defined by SAM as the follow:

$$P_{ac} = \left[\frac{P_{ac,0}}{A - B} - C(A - B) \right] (P_{dc} - B) + C(P_{dc} - B)^2 \quad (4.38)$$

Where:

$$A = P_{dc} [1 + C_1(V_{dc} - V_{dc,0})] \quad (4.39)$$

$$B = P_{so} [1 + C_2(V_{dc} - V_{dc,0})] \quad (4.40)$$

$$C = C_0 [1 + C_3(V_{dc} - V_{dc,0})] \quad (4.41)$$

The meaning of the variables is:

- P_{ac} is the AC power produced in the output of inverter;
- P_{dc} is the DC power produced by entire plant and it included the cable losses arrives in the downstream of inverter;
- V_{dc} is the Direct Current voltage of the plant (includes the average voltage drop in the cable) in input of the inverter.

While the parameters available from the datasheets are all of those with a subscript equal to 0. The inverter's manufacturers give also the P_{S0} called inverter self-consumption and the $P_{,night}$ means the P_{ac} required by the inverter if it turned on during the night.

The coefficients with C are empirical in order to follow the real behaviour of inverter:

- C_0 : it makes in relation DC input power with AC output power.

- C1, C2, C3 are added to create a linear variation of the power parameters with the voltage.

Overall when the input voltage increase, the conversion from DC power to AC power, means its inverter efficiency, decreases.

If the C coefficient from experimental measurements is not available, all values of C are set to 0 and a new equation is used for calculating AC power:

$$P_{ac} = \left[\frac{P_{ac,0}}{P_{dc,0} - P_{so,0}} \right] (P_{dc} - P_{so,0}) \quad (4.42)$$

The Equation 4.42 described the linear correlation between Pdc and Pac without the dependency of DC voltage value. This model is used by Sandia Laboratories researches in [20].

As mentioned before, the inverter needs a minimum amount of DC power to starting the conversion into AC power. This power called self-consumption power and it is assumed the 1% of the Pdc,0. So, the efficiency became:

$$P_{ac} = \frac{P_{ac,0}}{P_{dc,0} - P_{so,0}} \left(1 - \frac{P_{s,0}}{P_{dc}} \right) \quad (4.43)$$

In this way, the efficiency increases with a growth of Pdc. Normally the behaviour of the efficiency is different from what is described in the Equation 4.43 because the maximum of the efficiency is around the 60 % of the rated Pdc. Meanwhile setting C0 given from a maximum efficiency at Pdc,in = 50% producing more accuracy, in this work C0 is equal to 0 in order to follow the original model of Sandia Laboratories explained as mentioned in [20].

It is important to consider also the power consumed by the inverter in the hours when the plant is turned off. For instance, during the night the P_{DC} is equal to zero but the inverter absorbs a power in order to stay on. Therefore, the considered model of efficiency sets

the night consumption equals to zero as the inverter has been switched off at the night and then, it returns on when the Sun rise.

Otherwise, during the day if the P_{DC} generated is minor than inverter consumptions, the power produced by the inverter is negative $P_{AC} = -P_{night}$ because the inverter is really on.

If the power production from the PV modules is larger than the maximum value of input power supported by the inverter ($P_{DC,0}$) there is a power clipping. The inverter clips the power when $P_{DC} > P_{DC,0}$ by changing the operational point of IV curve that goes away from maximum. The model stored the clipped power every hour in a vector in order to be useful, a further analysis on the real design of inverter coupling can be studied in order to optimize its operation.

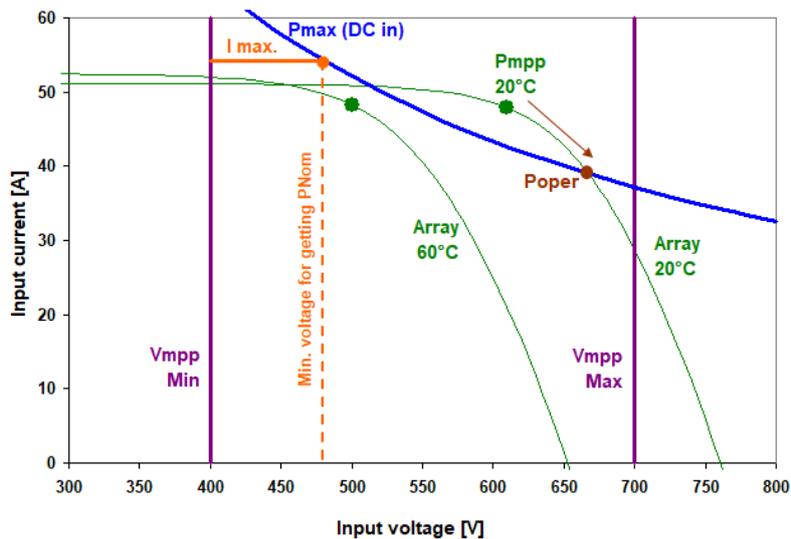


Figure 4.11: the shift of working point in the clipping of inverter [20]

Looking at the Figure 4.11 the different operating point are described, in particular:

- Above the blue curve there are the nominal inverter losses caused by higher P_{DC} (overload losses);
- Inverter losses out of the range between V_{min} and V_{max} (working conditions).
- The orange line shows the inverter losses due to maximum input current limit.

4.6 Model of energy production of the plant

In this section is described the approach to provide the energy production of the plant entering on the electric grid. From the previous model, the hourly AC power is calculated with related losses. So the unit of measure of energy is kWh and the calculating power in kW had a time step of one hour, so the measures not needed a unit conversion from hourly power to energy.

In order to take in mind how MATLAB model works, a briefly recap can be useful:

1. The GHI arrives through the atmosphere and it is arranged by the POA model in order to estimate the part that hits the module with the relating tilt and optical losses.
2. The second step is related on the conversion of the irradiance to electric power through equivalent circuit of the single diode model and T cell temperature's one.
3. The current produced by the strings of modules pass through the String Box and arrives downstream the inverter with a large sections solar cable calculated by the relative model.
4. Then, the DC cable losses model calculates the power losses and voltage drops for each String Box's cable and it is validated with the array mismatch losses model.
5. The DC power coming from all modules are converted in AC power with the model of inverter and introducing the inverter efficiency and then, its losses.

Overall, the energy yield introduced to the electrical grid can be calculated as described in Eq. 4.44:

$$E_{grid,yearly} = \sum_1^{8760} E_{grid,hourly} F_{availability} \quad (4.44)$$

The availability factor is introduced in order to take care about the failure issue during the year. This parameter considers the fact that for a certain hours of the year the plant is

unavailable [19]. For the further analysis this factor is fixed equal to 1 but there are many statistical analyses about the failure of a PV plant in order to modify this parameter.

It is important to underline the assumption made regarding the losses related to AC side of the plant (like as AC cables, transformers and other components) are not considered.

4.7 Financial model for the choice of cabling sizing

The scope of this model is making an economic estimation of the investment cost of one specific DC cable sizing against the revenues cash flow due to the energy savings of the cables' sections.

Firstly, one simulation is computed considering equal to zero the power losses and the voltage drops of the DC cables in order to have a sample of comparison. That first value is calculated avoiding the model of DC cable losses and array mismatch model. The model estimates the hourly P_{AC} of the entire plant through the SAM inverter sub-model explained in Section 4.5 of this work. The input parameters of sub-model are described in the equations 4.45 and 4.46:

$$V_{DC,input,no\ losses} = N_s * V_{mp} \quad (4.45)$$

$$P_{DC,input,no\ losses} = (N_s * V_{mp}) * (N_p * I_{mp}) \quad (4.46)$$

Then the energy yield is calculated summing, as shown in equation 4.47, all hourly P_{AC} values in the entire year.

$$E_{no\ DC\ losses} = \sum_1^{8760} P_{AC,no\ losses,i} \quad (4.47)$$

After that, another simulation is computed for a given voltage drop limit. In this case the P_{DC} in input of the inverter's sub-model is the power that considers the sum of all P_{DC} losses of the cables. Otherwise the V_{DC} considered as an input was the previous DC

voltage minus the maximum value between the voltage drop of the line cables. The correlations are shown in the Equations 4.48 and 4.49.

$$V_{DC,input,losses} = V_{DC,input,no\ losses} - \max(V_{drop,n-line}) \quad (4.48)$$

$$P_{DC,input,with\ losses} = P_{DC,input,no\ losses} - \sum_1^{N_{SB}} P_{loss,n-line,i} \quad (4.49)$$

The P_{AC} calculated in this case is less than the first one. Also in this case, the energy yield is calculated as summing the hourly P_{ac} production of the plant during the all operational hours of the year as shown in the equation 4.50.

$$E_{prod,with\ losses} = \sum_1^{8760} P_{AC,with\ losses,i} \quad (4.50)$$

At the end, the energy losses can be calculated as expressed in the equation 4.51:

$$E_{lost} = E_{no\ DC\ losses} - E_{pro,with\ losses} \quad (4.51)$$

At the same time, the model calculates the price of the layout of cabling for each voltage drop limit. Therefore, the module requires an input array in which is defined all prices for different section of cable necessary for building the plant layout in terms of [€/m].

Summing the money spent for each section, the total cost of DC cables is obtained.

For the scope of model, there is a necessity to convert the energy losses into an economical parameter. This estimation cannot be made a priori because the wholesale price of the energy sold to the electric grid network depends on the energy market of the country where the plant is located and the politics of the country's government. Then, it is calculated the total money lost in the entire plant lifetime by the Eq. 4.52.

$$cashflow_{lost} = E_{lost} * price_{MWh} * lifetime \quad (4.52)$$

However, the price per MWh produced of the plant and sold to the grid is obtained by a mean value of the previous year for the energy market of the country in which the plant is located.

By summing the cash flow lost and the initial investment cost for all $\Delta V\%$ cases the optimization curve is obtained. Its minimum represents the best configuration for the cable sizing as shown in Figure 4.11

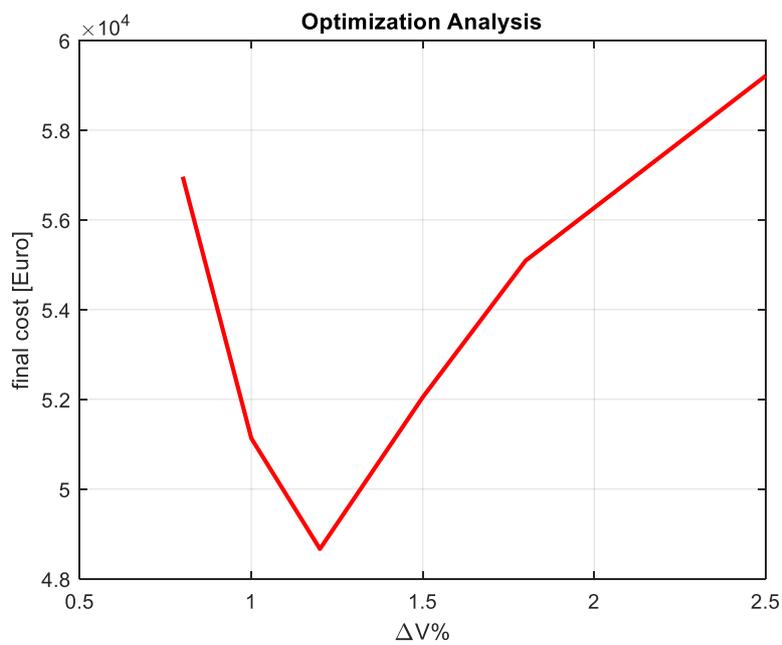


Figure 4.12: Example of optimization curve

6. Case Study: optimization of cabling sizing

In this chapter, a case study is considered in order to estimate the economic results in a project design changing the cabling sizing in a fixed PV plant layout.

It is important to remember that the current passing through the cables depends intrinsically on wires resistances. Therefore, for different resistances of the cables, there will be different currents passing through them. In this work the currents are considered the same for each cables that arrives into the inverter. This assumption is deeply explained in the Section 5.5 of this Chapter with a current analysis considering the array mismatch between the String Box's cables for a representative hour of the year.

5.1 Scope of Case Study

The objective of this analysis is the optimization of cabling sizing with a comparison between the cost of losses against the cable investment cost over the entire operational lifetime of the plant.

The contribution of DC cable losses in PV design is often one of the minor aspects of the problem and it is neglected. Normally the assumption of DC cable losses is approximated around 1-2 percent of the power production. The main causes of this losses are due to overheating and its corrosion during the plant lifetime.

This behaviour of neglecting the effects of well cabling in the plant design may lead to the installation of an inefficient PV plant for its entire life. In fact, choosing a set of solar cables with an oversized section will reduce the power losses, but it could be providing a large initial investment cost. This cost may be minimizing if there is a well design in the initial phase of the project.

For this reasons the implementation of this function in the MATLAB code can be very useful for all experts of the sector. Starting from the input data explained in the further sections, the software runs firstly a specific model of DC cable losses and then, the economic model with costs estimation provide the best cable sizing in terms of costs.

An important issue of the model is the performing of hourly DC cable losses and this provide an analysis with a high level of accuracy.

The analysis depends on the different parameters like as surface of PV plant, location, topology of the cabling and the size of PV plant.

5.2 Methodology of Case study

The optimization program is computed for different location. The DC cable losses model gives as outputs the different cabling configurations (for different fixed voltage drops) and their losses in terms of DC voltage drops and power losses.

The model of the DC cable losses starting for some choices:

- Layout of the plant (N_s , N_p and N_{SB});
- Type and number of channels of String Combiner Boxes;
- Fixed maximum voltage drop array in percentage;
- Cabling topology;
- Array wires' sections.

A previous model described in Section 4.2 shows all possible configurations of the plant. Choosing one of the possible configurations, the economic model is ready to run the simulation with another economic inputs that must be taken in consideration:

- Wires' prices for each section of cable per meter;
- Price of the energy [MWh] sold to the grid from the energy market of the country.

The model gives as output the total investment cost of the cables and total revenues of energy savings and it compares the value in order to choose the best sizing of cable in entire plant.

5.3 Hypothesis of the case study

In this case study the scope is to compare PV plant with the same design in different location. For this reasons the layout and the components installed are the same. The components are taken from a top solar manufacturing industries.

The Starting point of the design of PV plant is the choise of DC power of the plant:

- $P_{DC}=1000$ [kW]

After that it is possible to consider all components and design parameters.

5.3.1 Module

The module characteristics are taken from the datasheet elaborated by Sandia National Laboratories [16]. The module in this case study is the JinkoSolar 320PP-72. The module has a very high quality and the percentage of failure module is very low. Another reason is that the JinkoSolar industry is one of the most important player in PV module manufacturing.

5.3.2 Inverter

The inverter chosen is ABB ULTRA 1100 BBL. The first reason of the choice is the notoriety of ABB industry regarding electrical components for all uses. The second reason is the most worldwide spreading of this model of inverter means a high reliability.

The choice of inverter with the same size of the plant is due to simplify the layout and also increase the complexity of cabling topology. As shown in the Figure 5.1, the inverter chosen has the maximum efficiency for a higher value of V_{dc} in input. This is not usually the behaviour of the efficiency curve of inverter. Therefore, the results on the efficiency will be discussed in the further sections.

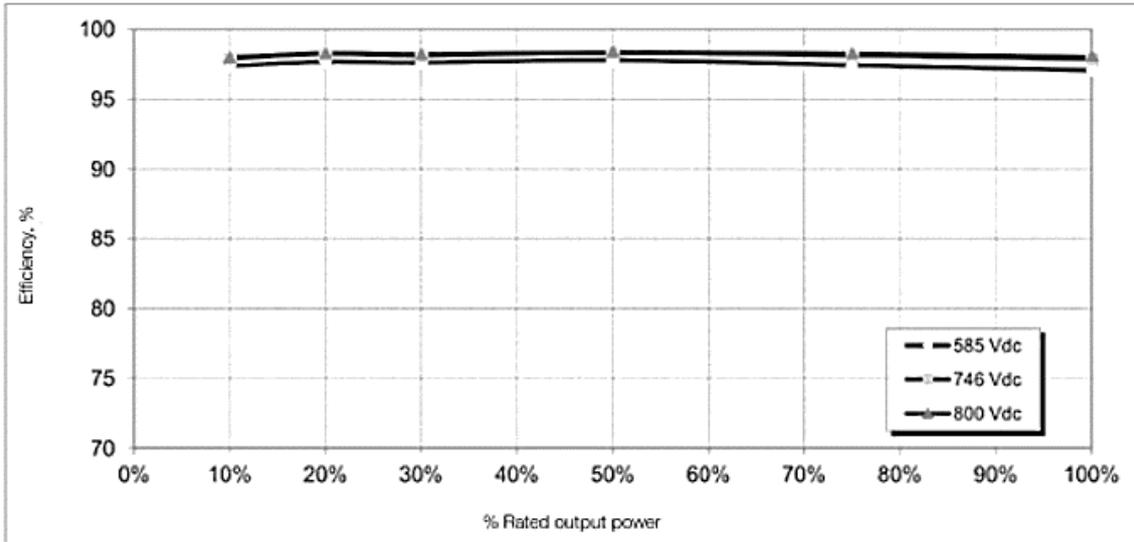


Figure 5.1 Efficiency of ABB ULTRA 1100 inverter [21]

5.3.3 String Combiner Box

The String Combiner Box is also from the ABB industry, coherent with an inverter in order to have the best connection between these components. This model of String Box controls the current passes through it, the internal temperature and it has all electrical protection in order to automatic disconnect the strings in case of damage. The maximum supported DC Voltage is 1000 [V]. The main important data is the number of string that it can connected equal to 12 in the chosen configuration.

5.3.4 Solar Cables

For the work of thesis, the choice of the specific solar cable has a main role. The characteristics of the cable determines the amount of the losses due the resistivity of its conductor. Therefore, it is considered the ambient conditions around the plant of the location means the moisture content and the capability for corrosion. The choice of the solar cable is focused on a cable with flexible tinned copper as conductor, insulated in ethyl-propylenic rubber under a PVC sheath [22]. The cable has a nominal voltage of 0.6/1 kV according to the voltage condition of the plant.

5.3.5 Plant layout

In the case study a specific configuration between the possible ones is chosen in order to have the same layout for every location. All parameters of the chosen configuration are described in Table 5.1.

<i>Parameters</i>	N_s	N_p	N_{SB}	V_{MIN}	V_{MAX}	<i># of modules</i>
<i>Value</i>	19	12	14	623.2	729.6	3192
<i>Unit</i>	-	-	-	Volt	Volt	-

Table 5.1 Configuration of the plant

The total number of strings are obtained by the N_p multiply for N_{SB} (number of String Boxes).

The selection of the plant layout is due to the model of inverter.

The selection between the more possibilities is due by behaviour of the inverter. In fact, the datasheet shows that the maximum efficiency curve around the V_{max} of array. As mentioning before, it is important to remember that the current generated by the string is the same of the current module in which performing badly. For this configuration array can be consider a good trade-off between these two aspects. The specific symmetrical layout is shown in the further section.

The figure 5.2 shows the plant layout.

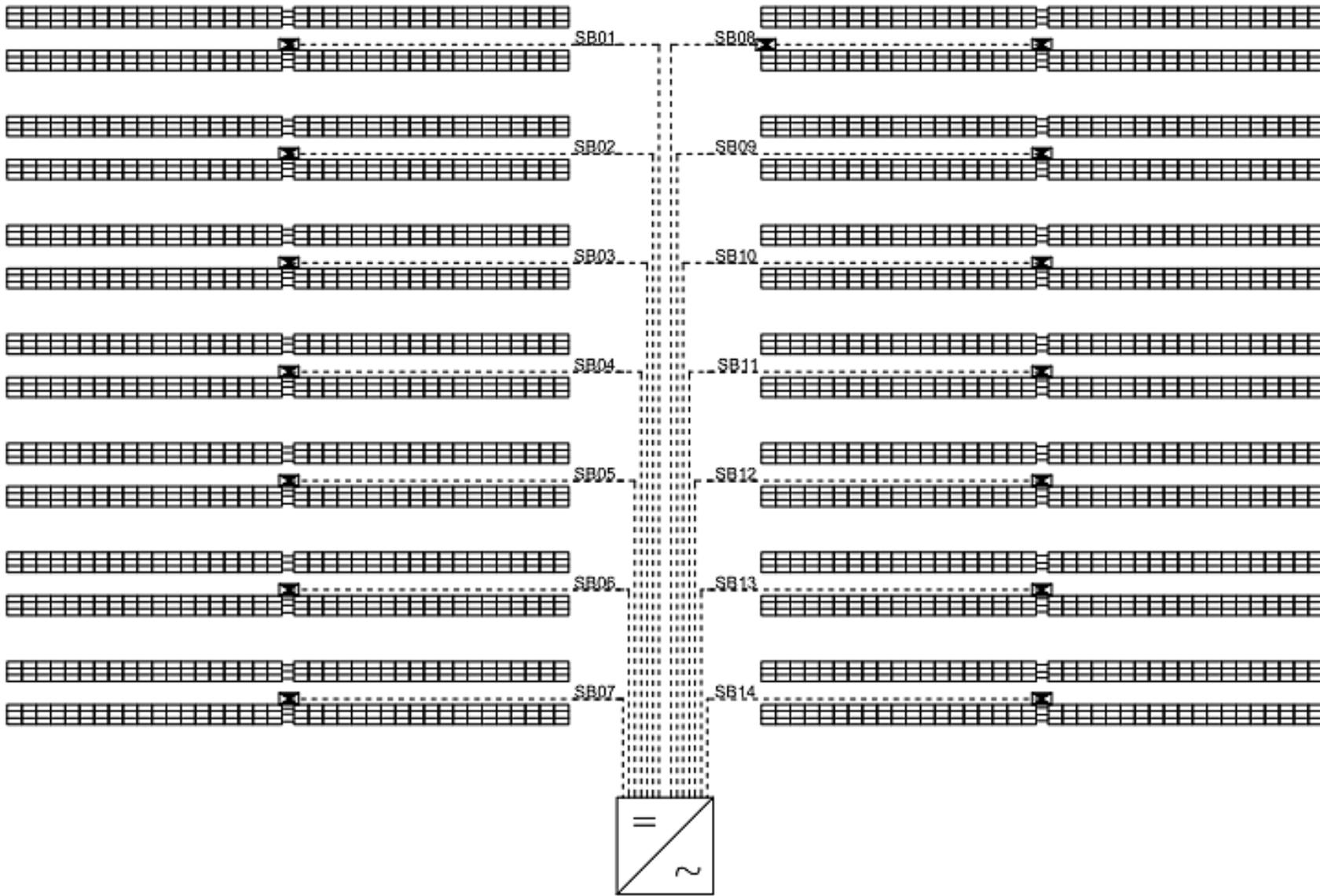


Figure 5.2 PV Plant topology

5.4 Input data for the models

To run the simulation until the calculation of I-V curve of module, all sub-models need the input parameters described in Table 5.2 which are deeply described in the Chapter 4. For this case study, it is considered a generic plant, the setting of the parameters is on their default values.

<i>Variable</i>	<i>Value</i>	<i>Unit</i>
<i>DHI/GHI</i>	from data [23]	-
<i>Albedo</i>	0,2	-
<i>b</i>	0,05	-
<i>SF</i>	1	-
<i>Alfa</i>	0,9	-
<i>U0</i>	29	W/m ² K
<i>U1</i>	0	W/m ² K/m/s
<i>Tmax</i>	60	°C
<i>Tmin</i>	20	°C
<i>Tmin,abs</i>	-10	°C
<i>F(availability)</i>	1	-

Table 5.2: input parameters for IV model

At this point, the DC cable losses model is computed. The model calculates all cable lengths from the strings of modules into the inverter. The dimension of module (module's length and module's width) is given by the datasheet of JinkoSolar in order to calculate the distance between rows as explained in Section 4.3.1. The section of the cable that connects the modules in series usually is standardized and it can be from 4 to 8 mm². For this case study the section of string cable is fixed on the value presents in the datasheet of the module. The module's length is used also for the estimation of the length of one string. In the Table 5.3 is shown all the requirements of the model:

<i>Variable</i>	<i>Value</i>	<i>Unit</i>
<i>d,row</i>	1,9	m
$\rho_{cs,0}$	0,0196	$\Omega\text{mm}^2/\text{m}$
<i>l,module</i>	1,64	m
α_{cu}	0,00395	1/°C
<i>w,module</i>	1	m
<i>Nc</i>	12	mm ²
<i>Dp</i>	3	m
<i>D₀</i>	10	m
<i>S_l</i>	4	mm ²

Table 5.3: parameters of DC cable losses model

The Table 5.4 describes the chosen of the maximum voltage drops reaching all cable lines that as an input data of the model. In order to compare different voltage drops, a reasonable range of ΔV_{dc} % are chosen in the project design. The percentage are referred on the mean value of DC voltage input during the operational hours of the plant.

<i>case</i>	<i>1</i>	<i>2</i>	<i>3</i>	<i>4</i>	<i>5</i>	<i>6</i>
$\Delta V_{dc}\%$	0,8	1	1,2	1,5	1.8	2

Table 5.4 Voltage drop limits array

A different sections of commercial solar cables are considered for the analysis of the different physical topologies. The model calculates the different cabling sizes for each voltage drop case and the lengths of the cable.

Finally, financial model can be computed. The model required as the input the result of the previous model plus the price of cables related of each sections. This kind of data are fixed in all simulations of the case study.

The specific solar cables sections taken for the analysis are shown by the Table 5.5:

Section	6	50	70	95	120	150	185	240	300	[mm ²]
Price	0,91	6,04	8,4	10,93	12,75	17,44	21,19	27,89	35,21	[€/m]

Table 5.5 Section and price of cable [22]

The other parameters needed to study the economic model is the lifetime of the plant assumed equal to 30 years.

The price of the energy sold at the grid depends on many factors in different weight for each country, like as the time when the energy is lead into the grid, the country's policy and the size of the plant. For simplify the analysis, the value of energy sold to the grid is fixed as a constant amount for entire lifetime plant but depends on the energy market of the specific Country.

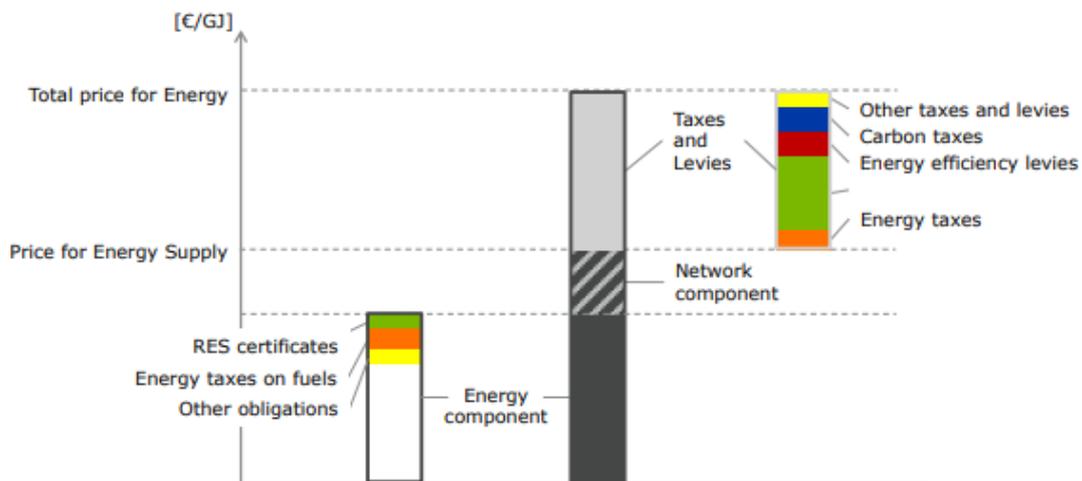


Figure 5.3 Components of the electricity price [24].

5.5 Current mismatch analysis

In this section it is analysed the difference between the currents that flow in the cables and its effect on the productivity of the plant. This phenomenon is called “currents cables mismatch”.

The analysis was first performed with the MATLAB model explained in Section 4.4 and then it is compared with an analytical model. The analytical model was created by using the fundamental concepts of electrical circuit theory. Applying the electrical theorem some equivalent circuits are created to modelling the problem up to the representation of the entire plant.

Then, the results of the two methods are compared and discussed, highlighting the most important aspects.

The cable parts involved in the analysis are highlighted in the Figure 5.4:

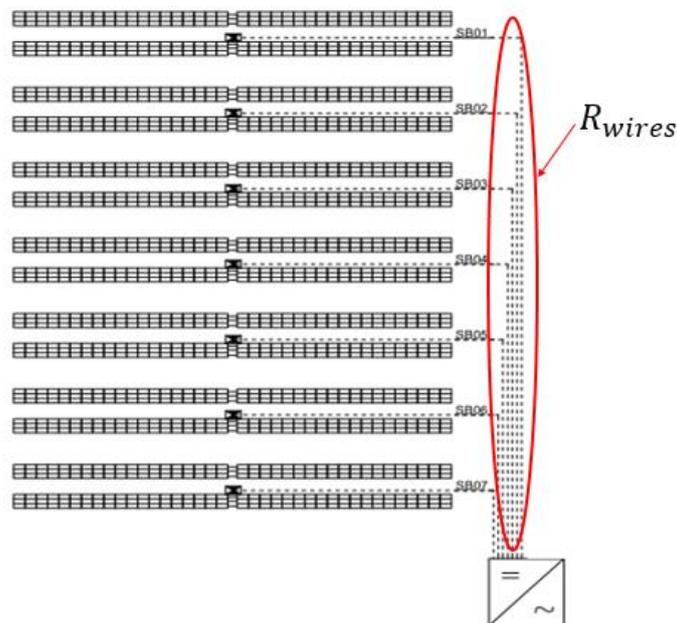


Figure 5.4 Wires resistances of the PV plant

In order to quantify the results of the mismatch model, a representative hour of the year is chosen with high irradiance in Barcelona in 2005.

In the hottest hour (15:00 pm) of the 17th July, the weather data are:

- Effective Irradiance= $925 \frac{W}{m^2}$
- Ambient Temperature = 304,5 K

5.5.1 MATLAB model results

Starting from the outputs of IV curve model a low section for the cable of array is chosen in order to recognize important changes in the PV power production. On the other hand, the sections of the cables are realistic and they are possible for the cabling of a PV plant.

The differences of the cable resistances are smoothly thanks to large section model explained in Section 4.3.

The Table 5.6 resumes the cables' values and their sections.

<i>Cable</i>	<i>SB01</i>	<i>SB02</i>	<i>SB03</i>	<i>SB04</i>	<i>SB05</i>	<i>SB06</i>	<i>SB07</i>	<i>Unit</i>
<i>R,cable</i>	0.393	0.386	0.379	0.389	0.38	0.388	0.375	Ω
<i>Length</i>	135,8	121,4	107	92,6	78,2	63,8	49,4	m

Table 5.6: Wires values of the case study

The cable sections are chosen to have a maximum voltage drop on the worst cable line minor than 1,8 % of the mean operating voltage of the inverter.

It is important to underline that the study regards only half of the plant due to its symmetry.

The Table 5.7 shows the wires' current calculated in the chosen hour. This results are generated running the simulation with the input layout data explained previously:

<i>Cable</i>	<i>SB01</i>	<i>SB02</i>	<i>SB03</i>	<i>SB04</i>	<i>SB05</i>	<i>SB06</i>	<i>SB07</i>	<i>Unit</i>
<i>I</i>	97.12	97.22	97.32	97.18	97.32	97.19	97.38	[A]

Table 5.7: Current flows in the wires

Then, the values of the currents are used to calculate the estimate power production of the plant. The maximum difference between the cables' current (mismatch) are calculated weighted on the maximum current as described in Eq. 5.1:

$$\%I_{mis,max} = \frac{I_{SB,max} - I_{SB,min}}{I_{SB,max}} * 100 \quad (5.1)$$

Therefore, another parameter that requires an accurate explanation is the power loss defined in the Eq. 5.2:

$$P_{loss,mis} = P_{no\ mis} - P_{tot,mis} \quad (5.2)$$

In the Eq. 5.2 the value of $P_{no\ mis}$ is calculated as the total power production if the mismatch is not present. This means that all cables from String Combiner Boxes to inverter have exactly the same resistance equal to the minimum resistance present in this case study.

$$P_{loss,mis} = P_{no\ mis} = f(R_{c,min}) \quad (5.3)$$

As a consequence, in percentage terms:

$$\%P_{loss} = \frac{P_{loss,mis}}{P_{tot,mis}} * 100 \quad (5.4)$$

All output results are shown in the Table 5.8:

<i>Output</i>	<i>Value</i>	<i>Unit</i>
<i>%I,mis,max</i>	0.2705	%
<i>P,max,array</i>	61,83	kW
<i>P,min,array</i>	61,67	kW
<i>P,tot,mis</i>	864.5	kW
<i>P,loss,mis</i>	1,24	kW
<i>%P,loss,mis</i>	0.143	%

Table 5.8: Outputs of simulation

In order to have a general point of view focused on this cables mismatch phenomena, the simulation is run for every hours of the year. The Table 5.9 shows the energy amount during one operational year:

<i>Output</i>	<i>Value</i>	<i>Unit</i>
<i>E,prod</i>	1772.8	MWh
<i>E,loss,mis</i>	1647.8	kWh
<i>Specific Energy</i>	1735.5	kWh/kWp
<i>% E,loss,mis</i>	0.0929	%

Table 5.9: Energy outputs per year

Where:

$$\text{Specific Energy} = \frac{E_{prod}}{P_{DC}} * 100 \quad (5.5)$$

In this case the P_{DC} is the number of module in the entire plant multiply for their Maximum Power in Standard Temperature Conditions. The Energy,loss,mis is a parameter representative of the impact of string mismatch on the energy production:

$$\%E_{loss,mis} = \frac{E_{loss,mis}}{E_{prod}} * 100 \quad (5.6)$$

5.5.1 Analytic Model

This model is created for a comparative analysis with a MATLAB mismatch model.

Basing on the results of IV curve solved by MATLAB program for the hour in the case study, the equivalent circuit is created applying the Thevenin generator.

The data resumed in the Table 5.10 are the output values of the IV curve model on MATLAB simulation:

<i>Data</i>	<i>Value</i>	<i>Unit</i>
<i>Impp</i>	8.115	A
<i>Vmpp</i>	33.4	V
<i>Voc</i>	41.252	V
<i>Isc</i>	9.06	A
<i>Ns</i>	19	-
<i>Np</i>	12	-
<i>NSB</i>	14	-

Table 5.9: Data from MATLAB IV model

The behaviour of a string of modules can be approximated linearly thanks to Thevenin theorem as shown in Figure 5.5 and the Results of the case study are calculated in 5.7 and 5.8:

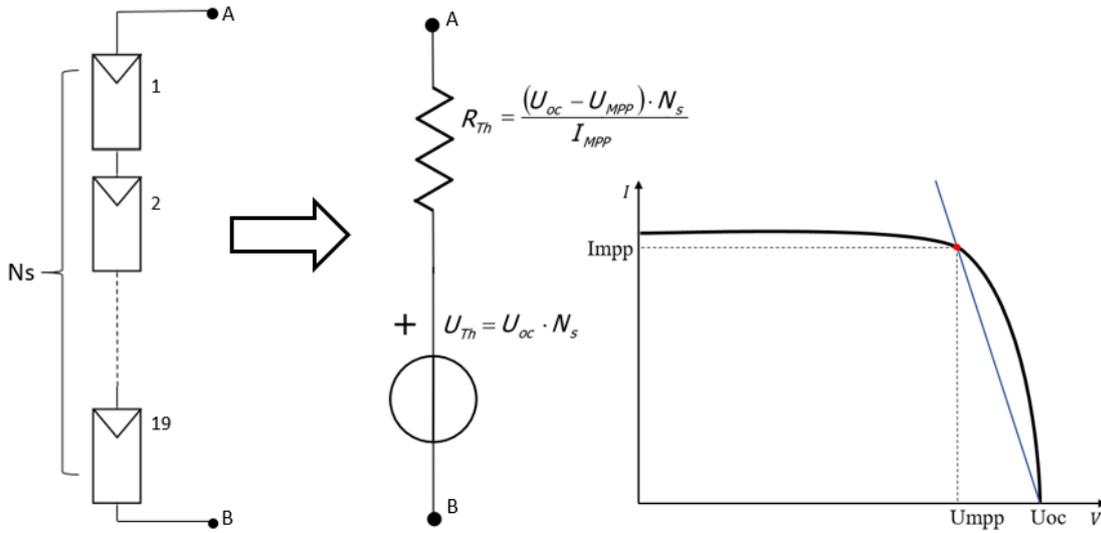


Figure 5.5: Application of Thevenin theorem for a modules' string [25]

$$R_{th} = \frac{(U_{oc} - U_{mpp}) * N_s}{I_{mpp}} = 18.384 [\Omega] \quad (5.7)$$

$$U_{th} = U_{oc} * N_s = 783.8 [V] \quad (5.8)$$

Then, the equivalent circuit of the String Box array can be modelled. Every string has the same voltage source equal to U_{th} and the same resistance R_{th} due to the assumption of a negligible differences of the length string cables. Applying the Thevenin theorem another time as Figure 5.6, the new equivalent resistance of array is easily calculated summing the current of all strings. The results of the method is shown in 5.9 and 5.10.

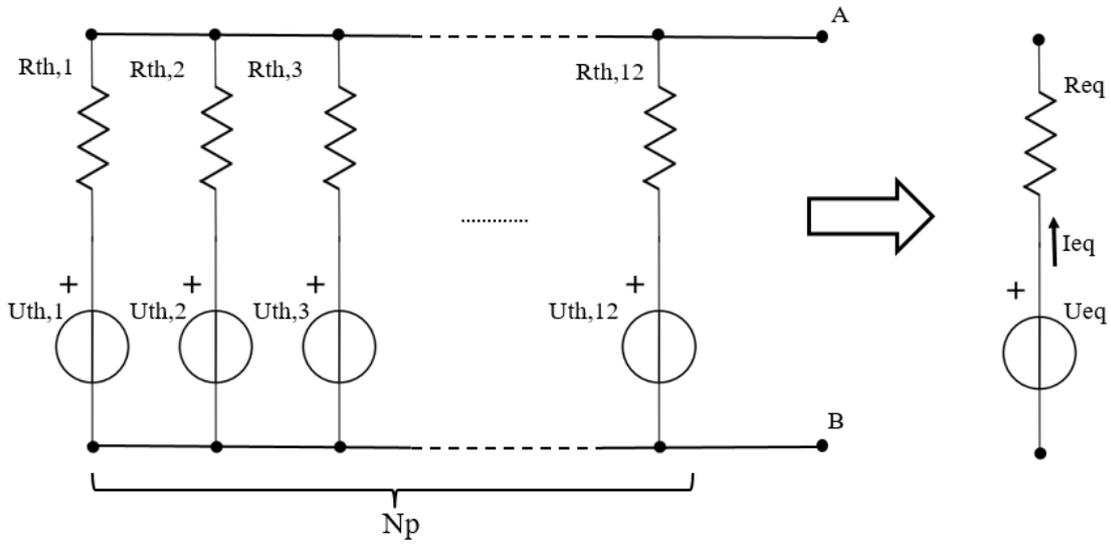


Figure 5.6: Application of Thevenin for SB array

$$I_{eq} = I_{mpp} * N_p = 97.38 \text{ [A]} \quad (5.9)$$

$$R_{eq} = \frac{U_{th}}{I_{eq}} = 1.532 \text{ [\Omega]} \quad (5.10)$$

At the end, all arrays are connected in parallel to the inverter. The entire plant is simplified by the equivalent circuit shown in Figure 5.7 where for each array's line it is added the related cable resistance. The inverter is considered as a load that works in its operating conditions taken from MATLAB output:

- $I_{MPPT} = 1363.3 \text{ [A]}$
- $V_{MPPT} = 634.6 \text{ [V]}$

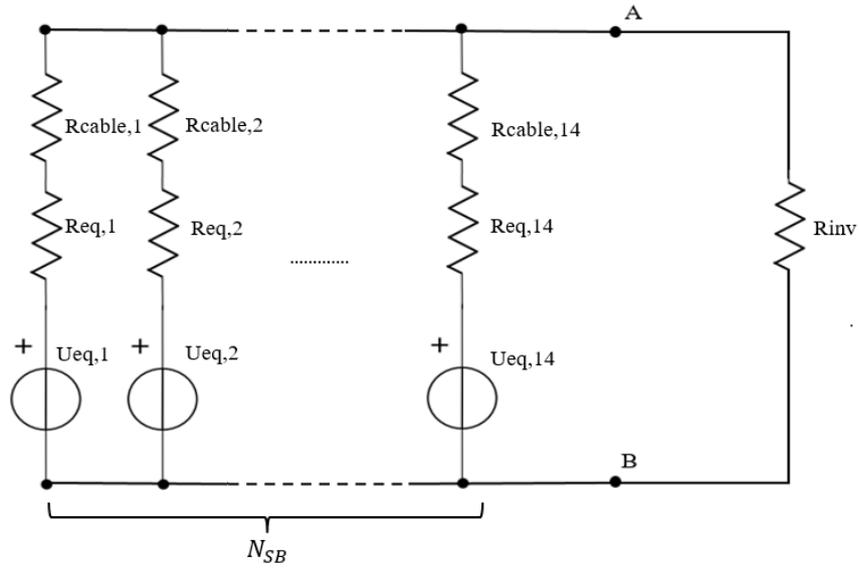


Figure 5.7: Equivalent circuit of the plant layout

The Millman theorem is applied on equivalent circuit described in Figure 5.7 in order to calculate every current that flows into the cables' array. It is important to remember that every voltage sources (U_{eq}) have the same value.

Firstly, the resistance in series of each cables is summed:

<i>Array</i>	<i>R cables [Ω]</i>	<i>R_{SB} [Ω]</i>
<i>SB 1 = SB 8</i>	0.4169	1.9489
<i>SB 2 = SB 9</i>	0.4076	1.9396
<i>SB 3 = SB 10</i>	0.3983	1.9303
<i>SB 4 = SB 11</i>	0.4142	1.9462
<i>SB 5 = SB 12</i>	0.4012	1.9332
<i>SB 6 = SB 13</i>	0.3881	1.907
<i>SB 7 = SB 14</i>	0.375	1.9489

Table 5.10: Values of cables resistances

In order to calculate the V_{AB} and solve the circuit is made a first approximation for the resistance of the inverter's MPPT that works in the Maximum Power Point:

$$R_{inv} = \frac{V_{MPPT}}{I_{MPPT}} = 0.4655 [\Omega] \quad (5.11)$$

At this point the V_{AB} value and, consequentially, the I of arrays can be calculated:

$$V_{AB} = \frac{2 * \left(\frac{U_{eq}}{R_{SB1}} + \frac{U_{eq}}{R_{SB2}} + \frac{U_{eq}}{R_{SB3}} + \frac{U_{eq}}{R_{SB4}} + \frac{U_{eq}}{R_{SB5}} + \frac{U_{eq}}{R_{SB6}} + \frac{U_{eq}}{R_{SB7}} \right)}{2 * \left(\frac{1}{R_{SB1}} + \frac{1}{R_{SB2}} + \frac{1}{R_{SB3}} + \frac{1}{R_{SB4}} + \frac{1}{R_{SB5}} + \frac{1}{R_{SB6}} + \frac{1}{R_{SB7}} \right) + \frac{1}{R_{inv}}} = \quad (5.12)$$

$$= 604.55 [V]$$

$$I_n = \frac{U_{eq} - V_{AB}}{R_n} \quad (5.13)$$

The coefficient 2 in Eq. 5.12 considers the plant as a whole.

The Table 5.11 describes the values of every current of array calculated with this approach:

<i>Array</i>	<i>I_{SB} [A]</i>
<i>SB 1 = SB 8</i>	91.97
<i>SB 2 = SB 9</i>	92.4
<i>SB 3 = SB 10</i>	92.85
<i>SB 4 = SB 11</i>	92.1
<i>SB 5 = SB 12</i>	92.715
<i>SB 6 = SB 13</i>	93.34
<i>SB 7 = SB 14</i>	93.98

Table 5.11: Values of array currents that flow through the wires

At the end, the most important parameters are evaluated for the consideration of the cable mismatch phenomena;

$$\%I_{mis,max} = \frac{I_{max} - I_{min}}{I_{max}} * 100 = \frac{93.98 - 91.97}{93.98} * 100 = 2.15\% \quad (5.14)$$

$$\%P_{loss,mis} = \frac{\sum_i^{NSB} I_i V_{AB} - N_{SB} I_{SB,min}}{\sum_i^{NSB} I_i V_{AB}} = 0.863\% \quad (5.15)$$

5.5.3 Comparison of results and conclusion

The results obtained by the approximation with the analytic method described in the last section is less accurate than the MATLAB model. The causes of the gap between the two methods can be related on the behaviour of the module. The difference is due to the linear approximation shown in Figure 5.5 and the approximation of the resistance of the inverter calculate roughly from its MPPT in Eq. 5.11.

On the other hand, in the analytical case the power losses are less than 1% of the total power produced by the plant; while in the computational solution the amount of power losses is less than 0.2%. In addition, the most accurate MATLAB model gives back an energy lost during one operational year minor than 0.1%.

The low impact of wires mismatch on the power production can be considered a not relevant effect.

Overall the assumption to consider the same average current for every String Box array can be considered justified.

5.5 Results

This Section is focused on the PV plant located in Barcelona as reference case study.

The simulation is run with the input parameters mentioned before. The layout of the plant is the same for all case means also the lengths of cable are the same in all simulations. The case study has a symmetrical layout, while the model calculates the lengths of the cable concerning only one side of the plant. For the cables placed on the other side, both

lengths and losses are the same. To calculate the results concerning the entire plant, the outputs are multiply for a factor of 2. It is important to remember the Figure 5.2 that represents the entire layout of the plant with all string boxes identifying the starting point of the wires of array.

Running the simulation, the model gives in output the lengths of the line cables from String Boxes to inverter and the length of one string. As mentioned before, all strings have the same length until the relative String Combiner Box. The Table 5.12 shows the lengths output for the layout of the case study.

	<i>string</i>	<i>SB 01</i>	<i>SB02</i>	<i>SB03</i>	<i>SB04</i>	<i>SB05</i>	<i>SB06</i>	<i>SB07</i>
<i>Length [m]</i>	36,96	135,8	121,4	107	92,6	78,2	63,8	49,4

Tables 5.12 Lengths of cables from String Boxes to inverter

Once the simulation is run, it calculates the minimum cross section of each cable in order to generate a voltage drop included in the fixed voltage drop limit.

In order to have an idea regarding the magnitude of the played voltage limits, a recap Table 5.13 shows the absolute voltage limit drops in this case study.

$\Delta V\%$	<i>0,8</i>	<i>1</i>	<i>1,2</i>	<i>1,5</i>	<i>1.8</i>	<i>2</i>
<i>V drop [V]</i>	5,52	6,9	8,28	10,35	12.42	13.8

Table 5.13 Absolute voltage limits [V]

The choice of this range of voltage drops guarantees a better equilibrium between a good performance of the plant and a reasonable investment cost of the cables.

A minor value of voltage drop limit requires a higher sections of cables that not justify their investment cost respect their energy savings. On the other hand, a higher value of voltage drops causes more energy losses that implies an inefficient PV power plant.

The outputs of the model are described in Table 5.14 with all possible cables sections for every voltage drop expressed in meters:

<i>cable lines</i>	<i>L SB01</i>	<i>L SB02</i>	<i>L SB03</i>	<i>L SB04</i>	<i>L SB05</i>	<i>L SB06</i>	<i>L SB07</i>
$\Delta V=0,8\%$	300	300	240	240	185	150	150
$\Delta V=1\%$	185	185	185	150	120	120	95
$\Delta V=1,2\%$	150	150	120	120	95	95	70
$\Delta V=1,5\%$	120	95	95	95	70	70	50
$\Delta V=1,8\%$	95	95	70	70	70	50	50
$\Delta V=2\%$	95	70	70	70	50	50	50

Table 5.14 Cable sizing for each voltage limits

For each given configuration, the model estimates the power losses generated from two contributions; the strings with a small sections' cables and the wires with a large section from SB to inverter. Considering the results, it is in evidence the contribution of this two components of power losses. In fact, the losses due to the string cables is not negligible because contributes for more than the 30% of the total losses of each line cables.

The Table 5.15 shows the corresponding cable resistances for each voltage drop limits.

	<i>SB 01</i>	<i>SB 02</i>	<i>SB 03</i>	<i>SB 04</i>	<i>SB 05</i>	<i>SB 06</i>	<i>SB 07</i>
$\Delta V\%=0.8$	0,3469	0.3447	0.3468	0.3441	0.3460	0.3464	0.3462
$\Delta V\%=1$	0,3601	0.3566	0.3595	0.3552	0.3571	0.3585	0.3609
$\Delta V\%=1.2$	0,3682	0.3734	0.3680	0.3723	0.3654	0.3702	0.3609
$\Delta V\%=1.5$	0,3929	0.3860	0.3791	0.3889	0.3796	0.3881	0.3750
$\Delta V\%=1.8$	0,4169	0.4076	0.3983	0.4142	0.4012	0.3881	0.3750
$\Delta V\%=2$	0,4534	0.4404	0.4273	0.4142	0.4012	0.3881	0.3750

Table 5.15 Wires' resistances [Ω]

The minimum value of commercial section of the cable is equal to 50 mm².

The value of yearly overall efficiency of the inverter has a very slight difference between voltage drop limit cases in the order of 0.02%.

Then, an economic model is running in order to estimate the initial investment cost for each cabling sizing cases. The model calculates the total demand of length of the cable for each section and multiply it for the correspondent price. The output of the simulation can be seen in the Table 5.16:

$\Delta V\%$	<i>Euro</i>	<i>Energy losses per year [MWh/y]</i>
0.8	42963	7,33
1	38303	9,15
1.2	31714	11,87
1.5	26487	13.68
1.8	25015	16.07
2	23203	20,16

Table 5.16 cost of cables and energy losses

Choosing a specific cable sizing, the model calculates the energy yield of the PV plant and its energy losses during the year respect the ideal case without cable losses.

For the Barcelona's case study, the cost of energy sold to the grid is assumed equal to 64 €/MWh given by the yearly average price of energy in 2018 in Spain [26]. Once the energy losses for entire plant lifetime is converted in money terms, a comparison between the two economic amount gives the better cables sizing in terms of money savings. An example for the case study is represented in the Figure 5.8.

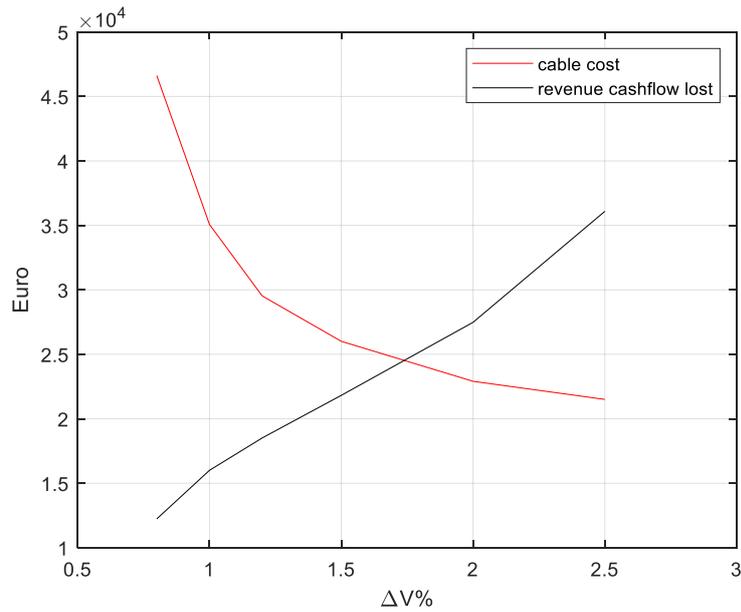


Figure 5.8: Comparison between cable cost against the cost of energy losses

In the left part of the Figure 5.8 the initial investment cable cost is larger than the revenue losses (red line). The reason is that the cable with a higher section have higher cost. In the intersection of the curves, the cost of wires is recovered with the energy savings in the entire plant lifetime. In the right part, the initial cable cost reaches its minimum but it does not cover the money spent due to energy losses. The next graph shown in Figure 5.9 sums both contributions in order to estimate the optimal cable sizing with a minimum final cost.

To summarize the results obtained in the simulation, an optimization curve is created. It is able to highlight the best configuration for the case study. The formula for the creation of optimization curve is explained in Eq. 5.16:

$$OPT = CABLE\ COST - ENERGY\ LOST * PRICE_{MWh} \text{ [€]} \quad (5.16)$$

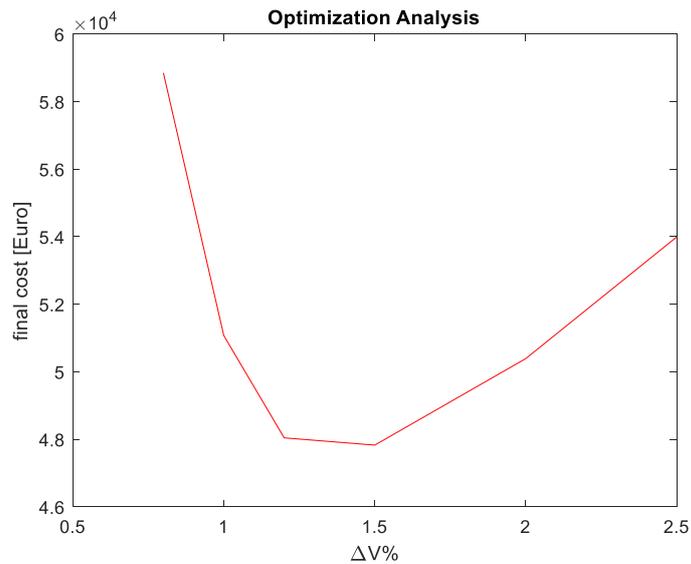


Figure 5.9: Final cost losses related to cable sizing choice

Overall, the optimization analysis mainly depends on the wholesale price of the energy sold to the grid of the country. This means that the country where is the plant has a main role on the effect of the optimization analysis if different countries are compared.

5.6 Comparison for different location

For the results of the case study, the simulation is computed for several locations basing on the different yearly average irradiance. Another representative parameter is the price of energy sold to the grid in order to have an idea about the impact of both the contributions in the optimization balance.

The typology of the choice of locations is focusing on the most representative locations compared to the reference one (Barcelona):

- Granada is a city in the South of Spain with a higher Irradiance and same policies than Barcelona.
- Naples is a city in the South of Italy with the same irradiance of Barcelona but with a different price of energy due to the different country.

The Table 5.17 shows the coordinates and the average Global Horizontal Irradiance (in kWh/y) for every location taken in the comparison:

<i>Location</i>	<i>Barcelona</i>	<i>Granada</i>	<i>Napoli</i>
<i>Latitude</i>	41,39	37,19	40,50
<i>Longitude</i>	2,17	-3.61	14,15
<i>GHI [kWh/y]</i>	1614	1875	1609

Table 5.17 General parameters of locations

The price of energy sold to the grid by the PV power plant is taken from the electrical supplier of each country through a mean monthly values of the 2018. The agency that have a role of arbiter on the electricity market are GME (Gestore Mercati Energetici) and OMIE (Operador del Mercado Ibérico de Energía) for Italy and Spain respectively.

The Table 5.18 shows the calculation of the energy price sold to the electric grid:

<i>2018</i>	<i>GME</i>	<i>OIME</i>
<i>January</i>	44,91	58,42
<i>February</i>	51,79	62,04
<i>March</i>	52,24	49,92
<i>April</i>	46,93	51,2
<i>May</i>	50,03	62,18
<i>June</i>	54,26	64,9
<i>July</i>	60,23	68,47
<i>August</i>	66,09	71,16
<i>September</i>	72,33	77,58
<i>October</i>	69,15	71,53
<i>November</i>	61,07	67,73
<i>December</i>	60,87	67,87
<i>Average</i>	57,5	64,42

Table 5.18 Calculation of the Average energy price [26] [27]

In the Figure 5.10 there is a comparison between the two cities of the Spain. The highest mean yearly Irradiance of Granada caused a larger slope on optimization curve.

The discretization of the optimization curve contains only 6 points equal to the values of voltage drops' vector. For this reason, to find a more accurate optimum point for Barcelona, the calculation should be iterated for lower voltage drop range between 1-1.5 $\Delta V\%$.

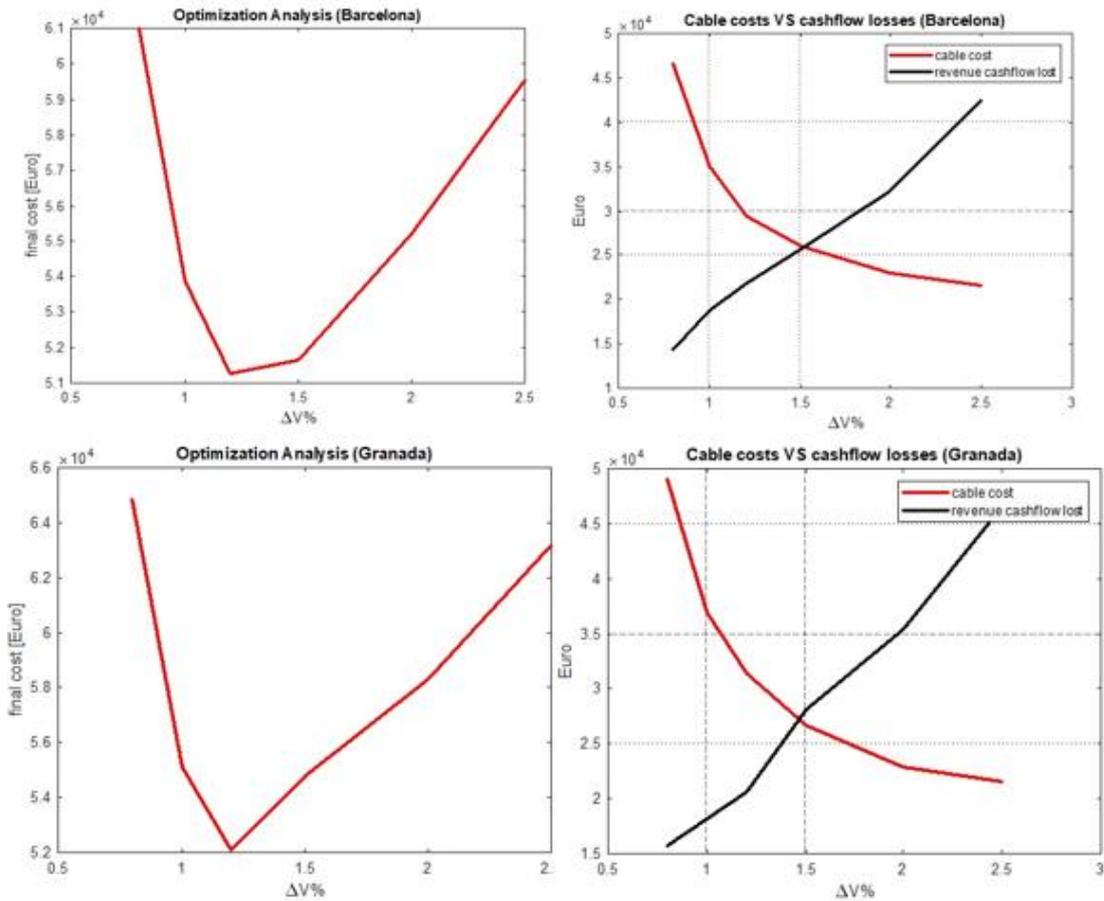


Figure 5.10 Comparison between Granada e Barcelona economic graphs

From the comparison between the two cost's curves described in Figure 5.10 on the second graph, it shows that the intersection is only moved on the x axis.

The Figure 5.11 plots the same outputs for Naples's case that have the same average Irradiance of Barcelona but the price of produced energy sold to the grid is lower than the Catalan city. The minimum point is shifted to high voltage drops around the 1.5 %. The

discretization of the curve is very rough, so the absolute amount of the final cost (in Euro) is not accurate.

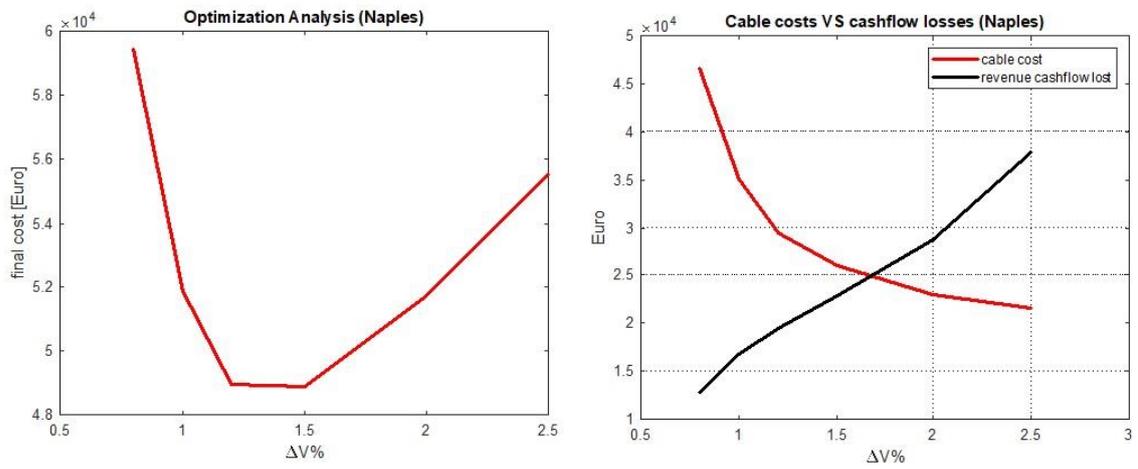


Figure 5.11 Optimization model results of Naples

6 Environmental impact of the PV plant

It is most important take care about the environmental issues caused by different power plant. Usually, to calculate the environmental effects for producing electricity the Life Cycle Assessment study is considered. The lower value of the LCA result is one of the major aspect that helps the growing of solar PV plant technologies. The study is focused on the 1 MW plant presented in the previous section and its environmental impact due to greenhouse gases emission in the entire life cycle. The environmental study permits to make a reasonable justification of the National and European policies related on subsidies for “clean” power plants and high taxes for the most polluting ones.

6.1 LCA analysis

The life cycle assessment takes into account all emissions for the specific technology from “cradle to grave” and involving the quantitative evaluation on its environmental impact in order to facilitate comparisons of power technologies. The LCA analysis consists of different steps and estimates the energy requirement and CO₂ emissions during the life cycle of the product.

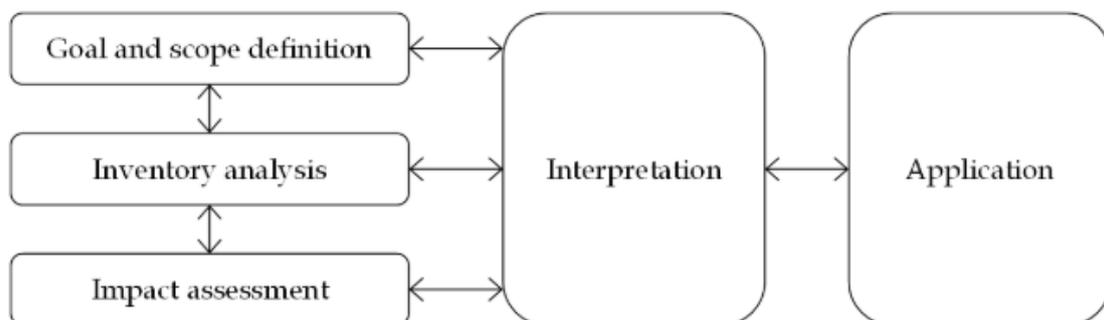


Figure 6.1 Different steps of the LCA analysis [28]

The calculation of LCA in deeply way is a complex topic because included the emission of all process starting from mining of Silicons, manufacturing process and plant construction. Also the transport used to move the raw material to the manufacturing plant affects the results. After that the LCA analysis is extended on the operational process of the plant like as system operation and maintenance. At the last part the study calculate the emissions related of plant decommissioning and the disposal of the module. More studies about the entire process have been carried out but the results are different. Each analysis depends mainly on the type of the technology of module, the control volume and thus the boundaries of the system study. A representation of the main process is described in the Figure 6.1.

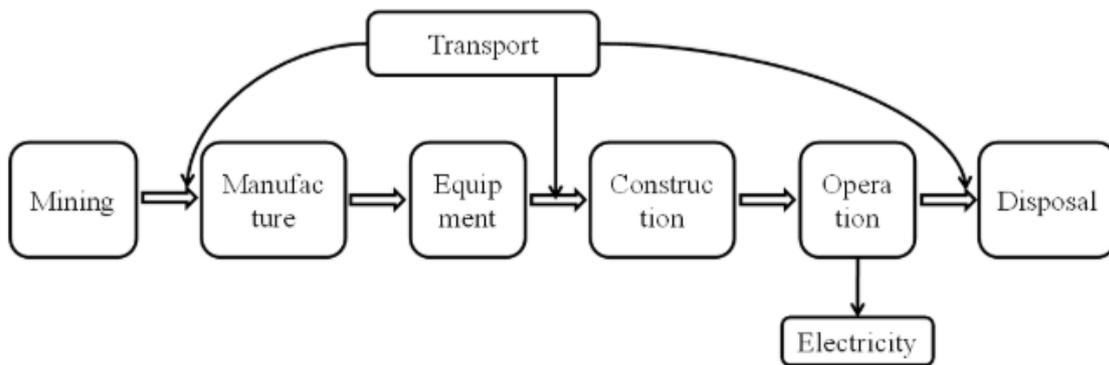


Figure 6.2: Boundaries of LCA analysis of a PV system [28]

As PV power plant produces electricity, one of the most useful parameter from carried out from LCA analysis is the energy payback time. EPT represents the number of years necessary to the system in order to recover the initial energy consumption involves in its entire life cycle. Another important result of the analysis is the Greenhouse gas emissions calculated in terms of CO₂ equivalents through the global warming potential approach in which all GHG substances turn into CO₂ equivalent with a conversion coefficient.

6.3 LCA guidelines for PV systems

Nowadays, there are a set of LCA guidelines for PV systems published by the International Energy Agency Photovoltaic Power System Programme (IEA PVPS). This report describes an important consideration for evaluating PV systems and making easy a comparison for different LCA on different PV plants.

- **Lifetime:** The standard lifetime for PV plant is difficult to quantify because many plants are in still operation but they are designed in the early stage of the technology's development. In general, the life expectancy of the PV system is a mean value of the published research. The Table 6.1 below shown the estimation of lifetime for the main component of PV plants.

PV modules *30 years for modern module technology*

<i>Inverters</i>	15 years for the small plants or domestic PV systems; 30 years with a 10% part of replacement every 10 years for large plants
<i>Structure</i>	30 years for rooftop plants Between 30 to 60 years for ground mounted installation in steel supports
<i>Cables</i>	30 years

Table 6.1 List of lifetimes of PV components [29]

- **Irradiation data:** the data of the irradiance depend on location and tilted angle of PV modules. There are two type of analysis in this sense; analysis of best case system and analysis on the average system connected on the grid network.
- **Performance Ratio:** the PR depends on the management of the PV plant means the hotspot phenomena on the string of array, and the type of installation and its monitoring in order to detect as soon as possible the defect or failure problems. In general, PR increase with low temperature on the plant and high maintenance. For the ground mounted with optimal installation the PR of the plant is set on 80%.

- Degradation: The degradation of the PV modules is an important topic of the recent year, especially for the thin-film PV system. A realistic value of degradation for crystalline silicon PV modules is 0.5 % per year (linear degradation). Regarding the guidelines for LCA analysis, it is considered the mature module technology have 80% of the initial producing capacity in the last lifetime year means 30th year of the PV plant.
- LCA data: the collection of LCA data is subdivided in foreground data and background data. Foreground types data are relative of the production process of the product like as foundation, cable manufacturing process, PV module manufacturing usually provided by producers. Background data are concerning the present raw material and their process of extraction and transport such as copper of the cable, array steel and the cement involved for the foundation.

6.2 PV plant emissions

In this analysis all the lifecycle emissions data derived from a study by Working Group about mitigation of Climate Change [30]. Considering all the stages for producing and operating utility solar PV system with a lifetime of 30 years, the median value of Greenhouse Gases Emissions is around 48 gCO₂eq/kWh [30]. The Figure 6.3 below shows a histogram graph that compare the lifecycle emissions for each technology of power plant.

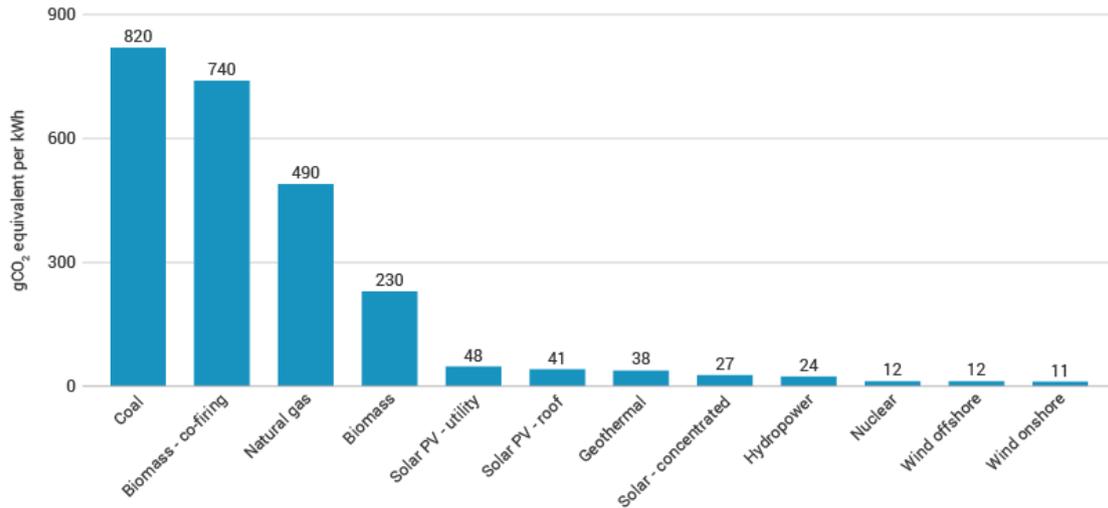


Figure 6.3 CO₂ equivalent emissions for different power plant technologies [30]

Looking the Figure 6.3 above it is clear that PV plants are not the lowest GHG emissive renewable technologies. The reason is to the mining and the disposal of the base material of the most common PV modules; Silicon. Nevertheless, the emissions of PV plants are always lower than all typology of fossil-fuel feeding power plants. Producing electricity from PV plant causes anyway a reduction of emission in any country because the highest part of electrical power production is made starting from fossil fuel.

For instance, in the better case the solar PV plant studied in Chapter 5 substituted a coal-fired power plant. For a resume the average emission of a coal plant is 820 gCO₂eq/kWh and the emission of a solar PV plant is 48 gCO₂eq/kWh. Thanks to the substitution of 1 MWe coal plant with a PV plant the overall avoided emission in entire lifetime of the plant will be:

$$\begin{aligned}
 & \text{Reduced CO}_2 \text{ emissions} \\
 & = \left(\frac{gCO_2eq, reduced}{KWh} \right) \times KW_e, PV \text{ plant} \times \frac{h}{y} \times \text{years CF} \quad (6.1) \\
 & = (820 - 48) \times 1000 \times 8760 \times 30 \times 0.197 = 39967,7 \text{ tons}
 \end{aligned}$$

Obviously, the energy mix of a country depends of the power plants technologies that supply the energy demand and they are different for each country. The previous result is far to realistic avoided emissions for any country. From a report of European Commission, it is defined a grid emission factor. This parameter considers the mean emissions of the specific technology which is weighted in proportion of its presence in the energy mix of the country. For example, taking the Italy's energy mix the value of grid emission factor is equal to 424 gCO₂eq/KWh [31]. Otherwise, the formula is applied for a solar PV plant in Barcelona as the first case study that has a factor of 343 gCO₂eq/KWh

$$\begin{aligned}
 \text{Reduced } CO_2 \text{ emissions} &= (343 - 48) \times 1000 \times 8760 \times 30 \times 0.197 \\
 &= 15272,6 \text{ ton}
 \end{aligned}
 \tag{6.2}$$

Of course, the quantitative impact of decreasing emissions depends mainly on the energy mix for each country.

Overall, most of the countries have an emission factor bigger than 40 gCO₂eq/kWh. This means that installing solar PV plants, in all cases, can reduce the GHG emissions of the country.

7 Conclusions

This work presents an optimization method to determine the optimal sizing of DC wires in a PV plant system, taking into account the total cost of cables and cables' losses across the lifetime of the PV plant. The scope is to create a model that determine the optimal size of solar cabling in PV system application. The approach used is based on the voltage drops produced by the wires and their losses on the production of the plant.

The proposed MATLAB program, based on the optimization model, is applied in a 1 MW PV plant located in Barcelona. The results provide an optimum cables sizing related to 1.2 % of maximum Voltage drop limits. For the optimum configuration the power losses, due to DC cables, correspond to 0.7% of the entire power production of the plant. A good sizing of the cables' cross section allows an equal resistance for cables with very different lengths. Using different cross section for the cables' topology of the plant, the current mismatch phenomena can be minimized. The maximum current mismatch obtained by the model is 0.27 %. From the comparisons carried out for different case studies, it can be seen that the optimum is always between 1% and 2% of the voltage drop limits. However, the price of energy sold to the electricity grid plays a very important role in the optimization model.

This project was implemented on MATLAB starting from a previous work, that is described in Section 4.1. Nevertheless, the MATLAB software created can be further developed by other students, in order to increase its accuracy, and to study in deeply a particular phenomenon of solar PV plant design. During the development of the software are introduced interesting topics that could be further studied. For instance:

- An integration of PV plant to the AC grid
- A model to retrieve the model parameters of I-V curve of the single diode model from measurements done at different T and G
- A study on the techno-economic strategy to design the optimum number of inverters and the best size of PV array.
- A model to consider the self-shading losses with high accuracy.
- A model that considers a Sun tracking module technology.

BIBLIOGRAPHY

- [1] IEA, “SNAPSHOT OF GLOBAL PHOTOVOLTAIC MARKETS”, 2018, page 6 [Online]. Available from: <http://www.iea-pvps.org/>
- [2] Photovoltaic Report of Fraunhofer ISE, 2018, page 5 [Online]. Available from: <https://www.ise.fraunhofer.de>
- [3] European Commission, “Energy Roadmap 2050, Impact assessment and scenario analysis “, 2011, [Online]. Available from: <https://ec.europa.eu/energy/en/topics/energy-strategy-and-energy-union/2050-energy-strategy>
- [4] IEA, “Photovoltaic Power Systems Programme - PVPS Annual Report 2016,” Int. Energy Agency, p. 130, 2016.
- [5] G. Fracastoro, “Energetica e fonti rinnovabili” slides’ course, 2014
- [6] A. Cabrera-Tobar, E. Bullich-Massagué, M. Aragués-Penalba, Oriol Gomis-Bellmunt, Topologies for Large Scale Photovoltaic Power Plants, 2017
- [7] “AVOCAB wires & cables” Website [Online] Available from: <http://www.avocab.com/products/solar-cables/>
- [8] H. Hizam, M. Reza Maghami, C. Gomes, M. A. Radzi, M. I. Rezadad and S. Hajighorbani, “Power loss due to soiling on solar panel”: A review, 2014.
- [9] G.N. Tiwari, Swapnil Dubey, “Fundamentals of Photovoltaic Modules and their Applications”, 2009
- [10] ITACA, The Sun as Solar Energy: The Atmosphere and Air Mass [Online]. 2016 Available from: <http://www.itacanet.org/the-sun-as-a-source-of-energy/part-2-solar-energy-reaching-the-earths-surface/>
- [11] K. J. Sauer and T. Roessler, “Systematic approaches to ensure correct representation of measured multi-irradiance module performance in PV system energy production forecasting software programs,” IEEE J. Photovoltaics, vol. 3, no. 1, pp. 422–428, 2013.
- [12] G. Catalano, “Development of a model to simulate solar PV plants in MATLAB with a study on the effects of undersizing the inverter” Master’s Thesis, 2018

- [13] A. Mermoud, “PVsyst 6 Help,” PVsyst SA, 2018. [Online]. Available from: <http://files.pvsyst.com/help/>.
- [14] Seaward Group USA, “Frequently asked questions about Curve Tracing.” [Online]. Available from: <http://www.seaward-groupusa.com/userfiles/curve-tracing.php>.
- [15] J. A. Duffie and W. A. Bekman, Solar Engineering of Thermal Processes. Wiley, 2013.
- [16] Database of Go Solar California Website [Online]. Available from: <https://www.gosolarcalifornia.org/equipment/inverters.php>
- [17] Library from Sandia National Laboratories Website [Online]. Available from: <https://sam.nrel.gov/libraries>
- [18] Deutsche Gesellschaft für Sonnenenergie, Planning and Installing Photovoltaic Systems: A Guide for Installers, Architects and Engineers, Revised, Update. Earthscan, 2007.
- [19] P. Gilman, A. Dobos, N. DiOrion, J. Freeman, S. Janzou, and D. Ryberg, “SAM Photovoltaic Model Technical Reference SAM Photovoltaic Model Technical Reference,” 2018.
- [20] D. L. King, S. Gonzalez, G. M. Galbraith, and W. E. Boyson, “Performance Model for Grid-Connected Photovoltaic Inverters,” Albuquerque, New Mexico 87185 and Livermore, California 94550, 2007.
- [21] ABB ULTRA inverter datasheet, [Online]. Available from: <https://new.abb.com/power-converters-inverters/solar/legacy/ultra>
- [22] COD: 06.P01.E02 Prezzario Regione Piemonte, 2018, page 1327 [Online]. Available from: <http://www.sistemapiemonte.it/cms/privati/territorio/servizi/929-consultazione-prezzario-regionale-opere-pubbliche/3427-prezzario-2018>
- [23] Weather data from SODA-PRO website [Online] Available: <http://www.soda-pro.com/web-services#radiation>
- [24] European Union, Ecofys Report [Online]. Available from: https://ec.europa.eu/energy/sites/ener/files/documents/report_ecofys2016.pdf
- [25] F. Spertino, ‘Power generation for renewable sources’ course’s slide, 2015
- [26] Operador del Mercado Ibérico de Energía, “Reports of monthly prices”, 2018 [Online]. Available from: <http://www.omie.es/en/home/publications>

- [27] Gestore Mercati Energetici, "Prezzi mercati elettrici", 2018, [Online]. Available from:<http://www.mercatoelettrico.org/It/Esiti/MGP/InformazioniPreliminariMGP.aspx>
- [28] Masakazu Ito, Crystalline Silicon - Properties and Uses, 2011 [Book]
- [29] ECN Solar Energy, Methodology Guidelines on Life Cycle Assessment of Photovoltaic Electricity - Subtask 20, "LCA", IEA-PVPS Task 12, 2009
- [30] Steffen Schlömer, Annex III of Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, 2014
- [31] European Commission, data related on 2013 from CoM Default Emission Factors for the Member States of the European Union, 2017

ANNEX 1

ARRAY MISMATCH MODEL: MATLAB SCRIPT

```
clear all
close all
clc

%% INPUTS single diode model

Pmpp=320; %[W]
N_cell=72; %cells in series
R_s=0.3646/N_cell;%resistence per cell
R_shunt=400/N_cell;%resistenza per single cell
I_stc=9.0582; % [A]
I_0_rif=1.8861e-10; %dark saturation current [A]
n=1.021; %ideality diode factor;
k=1.38e-23; %constant Boltzmann
q=1.60218e-19; %electronic charge
Eg_ref=1.121*q;
curve_points=100; %numberber of point of IV curve
number_of_array=14;
NOCT=45.5; %[°C]
alfa=0.0054; %[A/°C]
%grouped the variables
BBB=[N_cell];
B=n*k*N_cell/q;

%% INPUTS related to array layout of one SB
N_series=19; %modules in series
N_parallel=12; %modules in parallel

%% INPUTS related on whole PV plant

%% choose the n of inverter from Sandia database
load('CECInverterDatabaseSAM2015.6.30.mat')
Inverter_number=76;
Inverter_to_use=CECInverterDB(76); %1 MW
load VAR_Rcableequals %load cable resistance
R_cable=Rcableequals;
N_SB=length(R_cable); %stringbox in parallel
%% INPUTS weather data
load VAR_POA_GRANADA % load POA Irradiance
irradiance=POA_Effective_global;
load VAR_MeteoTable % load ambient T
T_amb=MeteoTable.AmbientTemp;

Tic

%% Calculation

%determionation of IV curve for a single module and a single SB arrayd
for cont_h= 1:1:length(irradiance)
if irradiance(cont_h)~=0
```

```

%determine the Tcell in function of ambient T(NOCT)
T_cell(cont_h)=T_amb(cont_h)+(NOCT-20)/800*irradiance(cont_h);

%Recalculate the I_0 function of Tcell
Eg=@(T)(Eg_ref.*(1-0.0002677.*(T-298.15))); % Band gap
I_0(cont_h)=I_0_rif.*(T_cell(cont_h)/298.15).^3.*exp((Eg_ref/298.15-
Eg(T_cell(cont_h))./T_cell(cont_h))./k);

%I_ph new function of T and irradiance
I_ph(cont_h)=irradiance(cont_h)/1000*(I_stc+alfa*(T_cell(cont_h)-
298.15));

%determine open circuit voltage at Tcell
Voc(cont_h)=B*T_cell(cont_h)*log((I_ph(cont_h))/I_0(cont_h)+1);

%calculate all point of voltage with equal distance
voltage_module=linspace(0.6*Voc(cont_h),Voc(cont_h),curve_points);

% grouped some variables
AAA=[I_ph(cont_h) I_0(cont_h) n R_s R_shunt T_cell(cont_h)];

%Solved numerically the IV curve with single diode model with Rsh and
Rs
current_module= IVcurve(voltage_module, AAA, BBB);

%determine the IV for the entire SB array without mismatch
current_stringbox=current_module'*N_parallel;
voltage_stringbox=voltage_module'*N_series;
for cont_stringbox=1:N_SB
voltage_drop_curve_array(:,cont_stringbox)=current_stringbox*R_cable(c
ont_stringbox);
voltage_on_inverter(:,cont_stringbox)= voltage_stringbox-
voltage_drop_curve_array(:,cont_stringbox);
standard_current_on_inverter(:,cont_stringbox)=interp1(voltage_on_inve
rter(:,cont_stringbox),current_stringbox,voltage_stringbox);
for cont_curve=1:length(voltage_on_inverter(:,cont_stringbox))
P_stringbox(cont_curve)=voltage_on_inverter(cont_curve,cont_stringbox)
.*standard_current_on_inverter(cont_curve,cont_stringbox);
end
max_P_stringbox(cont_stringbox)=max(P_stringbox);
pos_power(cont_stringbox)=find(P_stringbox==max_P_stringbox(cont_strin
gbox));
Imp_string(cont_stringbox)=standard_current_on_inverter(pos_power(cont
_stringbox),cont_stringbox);
Vmp_string(cont_stringbox)=voltage_on_inverter(pos_power(cont_stringbo
x),cont_stringbox);
end

%estimation of the power without mismatch 1
voltage_drop_curve_no_mismatch=current_stringbox*min(R_cable);
voltage_on_inverter_no_mismatch= voltage_stringbox-
voltage_drop_curve_no_mismatch;
power_no_mis_plant=voltage_on_inverter_no_mismatch.*current_stringbox*
N_SB;
power_max_no_mis_plant(cont_h)=max(power_no_mis_plant);
pos_max_no_mismatch=find(power_no_mis_plant==max(power_no_mis_plant));

```

```

%current estimation without mismatch
current_no_mis(cont_h)=current_stringbox(pos_max_no_mismatch);

%current mismatch
current_total_plant=sum(standard_current_on_inverter,2);
power_tot_plant=current_total_plant.*voltage_stringbox;
max_poower_tot_plant(cont_h)=max(power_tot_plant);
pos_max=find(power_tot_plant==max(power_tot_plant));
current_mismatch(cont_h,1:N_SB)=standard_current_on_inverter(pos_max,:
);
power_mismatch(cont_h,1:N_SB)=current_mismatch(cont_h,1:N_SB).*voltage
_stringbox(pos_max);

%data for inverter model
DCVoltage_array_hourly(cont_h)=voltage_stringbox(pos_max)';
DCPowers_array(cont_h)=max_poower_tot_plant(cont_h)';

%estimation percentage current mismatch max
for cont_perc=1:N_SB %%%
current_mismatch_percentage(cont_h,cont_perc)=...
(current_mismatch(cont_h,cont_perc)-
max(current_mismatch(cont_h,1:N_SB)))/(max(current_mismatch(cont_h,1:N
_SB)));
end

%estimation power mismatch
power_losses(cont_h)=power_max_no_mis_plant(cont_h)-
max_poower_tot_plant(cont_h);

else

end
end

%adding inverter model without mismatch
ACpower_sandia=JIA_sandia_inverter(Inverter_to_use,
DCVoltage_array_hourly, DCPowers_array);
for kk=1:length(ACpower_sandia)
if ACpower_sandia(kk)<0
ACpower_sandia(kk)=0;
end
end

%% output
plant_size=Pmpp*N_series*N_parallel*number_of_array/1000
annual_energy_mismatch=sum(max_poower_tot_plant)/1000
annual_energy_no_mismatch=sum(power_max_no_mis_plant)/1000
annual_energy_AC=sum(ACpower_sandia)/1000
eff_inv=annual_energy_mismatch/annual_energy_AC
yearly_power_loss=sum(power_losses)/1000
specific_energy_annual=sum(max_poower_tot_plant)/plant_size/1000
percentage_losses=yearly_power_loss/annual_energy_mismatch*100

% to simulate only for one hour of the year
irradiance_=irradiance(cont_h)
current_stringbox=current_mismatch(cont_h,1:N_SB)

```

```
min_current_stringbox=min(current_stringbox)
max_current_stringbox=max(current_stringbox)
power_stringbox=power_mismatch(cont_h,1:N_SB)/1000
min_power_stringbox=min(power_stringbox)
max_power_stringbox=max(power_stringbox)
```

```
toc
```