Electrical Methodology

A methodology to size the electrical equipment and the power cables of a photovoltaic plant

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Abstract

This electrical methodology explains the electrical calculations that the software does throughout the PV plant. It also explains the different criteria of each of the electrical cabling standards that pvDesign offers. The following topics are introduced in the methodology:

- The calculation of the maximum and minimum modules per string.
- The types of PV plant electrical configurations that pvDesign offers.
- The sizing of the equipment's protective devices such as fuses and breakers.
- The model that has been followed to size cables according to IEC and NEC standards.

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Chapter 1

Electrical equipment calculation

1.1 Number of modules per string calculation

The number of modules that can be connected in series in a PV plant is constrained by two conditions. The first condition is that the voltage of the modules must always be lower than the maximum input voltage of the inverter and the maximum module voltage. The second condition is that the voltage of the modules must be within the voltage range that maximizes the efficiency of the inverter.

The first condition marks the upper limit of the number of modules, and the second condition marks the lower limit.

The maximum voltage will be reached in low-temperature conditions when the modules operate at high efficiency. Therefore, based on the minimum operating temperature, the expression used to calculate the maximum number of modules in series is given by Equation 1.1.

$$Ns_{\text{max}} = \frac{V_{\text{max DC system}}}{V_{\text{oc}}(T_{\text{cell min}})} \tag{1.1}$$

It is necessary to calculate the open-circuit voltage of the PV cells as a function of their temperature using Equation 1.2.

$$V_{\text{oc}}(T_{\text{cell min}}) = V_{\text{oc}}(25^{\circ}C) + (T_{\text{cell min}} - 25) \cdot V_{\text{oc}}(25^{\circ}C) \cdot \frac{\mu}{100} \tag{1.2}$$

And the cell temperature is obtained from the minimum air temperature at the location, which is calculated using Equation 1.3.

$$T_{\text{cell min}} = T_{\text{air min}} \tag{1.3}$$

Where:

- Ns_{max} is the maximum number of modules per string.

- $V_{\text{max DC system}}$ is the minimum of the following values: maximum input voltage at the inverter, and maximum approved voltage of the module in [V].
- $V_{\text{oc}}(T_{\text{cell min}})$ is the open-circuit voltage of the cell at its minimum temperature in [V].
- $V_{\text{oc}}(25°C)$ is the open-circuit voltage of the cell at standard conditions in [V].
- μ is the module temperature coefficient of Voc in [%/°C].
- $T_{\text{cell min}}$ is the minimum temperature of the solar cells in [°C].
- $T_{\text{air min}}$ is the minimum historical value of air temperature at the location in [°C].

The second condition, which will define the minimum number of modules in series, is a function of the maximum temperature of the module cell. This temperature will be reached when the modules generate a higher voltage, in low ambient temperature conditions. Therefore, based on the minimum operating temperature, the expression used to calculate the minimum number of modules is given by Equation 1.4.

$$Ns_{\text{min}} = \frac{V_{\text{min MPPT inverter}}}{V_{\text{mp}}(T_{\text{cell max}})} \tag{1.4}$$

The open-circuit voltage of the photovoltaic cells and cell temperature are calculated using Equation 1.5.

$$V_{\text{mp}}(T_{\text{cell max}}) = V_{\text{mp}}(25°C) + (T_{\text{cell max}} - 25) \cdot V_{\text{mp}}(25°C) \cdot \frac{\mu}{100} \tag{1.5}$$

And, the cell temperature is obtained from Equation 1.6.

$$T_{\text{cell max}} = T_{\text{air max}} + I_{\text{max}} \cdot \frac{T_{NOCT(°C)-20°C}}{800\ W/m^2} \tag{1.6}$$

Where:

- Ns_{min} is the minimum number of modules per string.
- $V_{\text{min MPPT inverter}}$ is the minimum voltage of the MPPT voltage range of the inverter in [V].
- $V_{\text{mp}}(T_{\text{cell max}})$ is the voltage at the maximum power of the module at standard conditions in [V].
- $V_{\text{mp}}(25°C)$ is the open-circuit voltage of the cell at standard conditions in [V].
- μ is the module temperature coefficient of Voc in [%/°C].
- $T_{\text{cell max}}$ is the maximum temperature of the solar cells in [°C].
- $T_{\text{air max}}$ is the maximum historical value of air temperature at the location in [°C].
- $T_{NOCT(°C)-20°C}$ is the nominal operating cell temperature (45 °C), measured at 800 W/m^2 irradiance, with spectral distribution AM 1.5 G, air temperature 20 °C and wind speed 1 m/s.
- I_{max} is the maximum irradiance in [W/m^2]. It equals 1000 [W/m^2].

1.2 Electrical configuration

pvDesign offers four types of electrical configurations in the case of central inverters and two in the case of string inverters.

In the case of central inverters:

- String Box: The strings of modules are connected to a string box. And groups of string boxes are connected to central inverters. The number of strings per string box ranges from 4 to 36.
- Bus System: The strings are connected to a DC Bus collector and the connections reach the inverters. The number of strings per DC Bus collector ranges from 4 to 36.
- String Box L2 (Field): The strings are connected to string boxes which are connected to another level of string boxes which we call L2 that are located in the field. And groups of these are finally connected to the central inverters. The number of strings per level 1 string box varies from 4 to 16. And the number of level 1 string boxes per level 2 string box ranges between 12 and 16.
- String Box L2 (Station): The strings are connected to string boxes which are connected to another level of string boxes which we call L2 that are located in the power stations. And groups of these are finally connected to the central inverters.

In the case of string inverters:

- String Inverter (Field): The strings are connected directly to the string inverters. The string inverters are located in the field (outside the power stations).
- String Inverter (Station): The string inverters, in this case, are located in the power stations.

1.3 Protective devices

1.3.1 Fuses

The fuses of the LV DC side must meet the following conditions:

1. The fuse current must be greater than or equal to 1.56 times the module's short circuit current.

$$I_{\text{fuse}} \geq 1.56 \cdot I_{\text{sc}} \tag{1.7}$$

2. The fuse current must have a value between the cable's load current and its maximum current capacity.

$$I_{\text{load}} \leq I_{\text{fuse}} \leq I_{\text{ccc}} \tag{1.8}$$

Where:

- I_{fuse} is the rated current of the fuse in [A].
- I_{sc} is the short-circuit current of the PV module for string cables and the short-circuit current of the PV module multiplied by the number of strings per box/DC bus collector for upper PV plant levels in [A].
- I_{load} is the load current through the cable in [A].
- I_{ccc} is the maximum current capacity of the cable in [A].

1.3.2 Breakers

To size the on-load circuit breaker, the following conditions must be considered:

1. The switch current rating must be greater than or equal to 1.25 times the module's short circuit current.
$$I_{\text{breaker}} \geq 1.25 \cdot I_{\text{sc}} \tag{1.9}$$
2. The switch current rating must be less than or equal to the maximum current capacity of cables.
$$I_{\text{breaker}} \leq I_{\text{ccc}} \tag{1.10}$$

Where:

- I_{breaker} is the rated current of the breaker in [A].
- I_{sc} is the short-circuit current of the PV module for string cables and the short-circuit current of the PV module multiplied by the number of strings per box/DC bus collector for upper PV plant levels in [A].
- I_{ccc} is the maximum current capacity of the cable in [A].

Chapter 2

Distribution of strings into inverters and power stations

This section explains how strings are distributed into inverters and power stations in pvDesign.

This distribution will be influenced by many aspects:

- The equipment defined such as PV module, inverter, structure and power station.
- The number of modules per string.
- The maximum number of structures that can be installed in the area, along with the number of strings defined per structure. Strings from one structure will always be connected to the same inverter.
- The power requirements like the distribution preferences and the desired DC/AC ratio.

It is important to also mention that areas cannot be connected electrically in pvDesign, so strings from one area must be connected to inverters defined in that area.

2.1 Definition of possible power stations

There are two types of power stations that will be defined:

1. Default power stations: power stations that will be prioritised in the plant, installing as many as possible. Default power stations are defined by users.
2. Non-default power stations: power stations that will be installed in the case that the strings remaining are not enough to fill one additional default power station. The order of priority when installing them will be determined by the AC power of the non-default power station. The definition of non-default power stations will depend on the type of inverter defined.
    - Central inverters: all the possible combinations of inverters that do not exceed the total amount of inverters defined in a default power station nor the maximum value defined for one type of inverter.
    - String inverters: all the possible combinations within the limits defined by the user.

2.2 Calculation of the resulting power stations

The calculation of the resulting power stations installed will be done based on the power requirements:

1. Maximum capacity: install the maximum AC power in the design. There can be two modes of simulation:
    - Obtain the desired DC/AC ratio: this option ensures that the DC/AC ratio defined by the user is matched in every area, but may result in structures uninstalled due to incompatible electrical configuration.
    - Install the maximum peak power: this option ensures that the maximum peak power is installed for every area, always having a resulting DC/AC ratio that does not exceed the limits of ±0.15 with respect to the desired one.
2. Specific capacity: install a specific AC power in the design by defining the number of inverters of each type desired. It will ensure that the DC/AC ratio defined by the user is matched in every area.

This calculation will give as result the power stations that will be installed and the total number of strings per area. The later step will define the distribution of strings into inverters.

2.2.1 Maximum capacity obtaining the exact DC/AC ratio

This option ensures that the maximum AC power is installed, obtaining as result the desired DC/AC ratio in every area.

For every possible power station, starting with the default one and following with the non-default ones, the number of power stations installed is calculated by Equation 2.1.

$$N_{\text{PS}} = Floor\left(\frac{P_{\text{DC,available}}}{P_{\text{AC,PS}} \cdot R_{\text{DC/AC, desired}} + P_{\text{DC,embedded}}}\right) \tag{2.1}$$

Where:

- N_{PS} is the resulting amount of the power station in evaluation to install.
- $P_{\text{DC,available}}$ is the DC power available. It is recalculated considering power stations that have been already installed.
- $P_{\text{AC,PS}}$ is the active AC power of the power station in evaluation.
- $R_{\text{DC/AC, desired}}$ is the desired DC/AC ratio.
- $P_{\text{DC,embedded}}$ is the DC power loss relative to one embed power station (if applicable).

The total number of strings installed is calculated by Equation 2.2.

$$N_{\text{strings,area}} = Round\left(\frac{P_{\text{AC,comb}} \cdot R_{\text{DC/AC, desired}}}{P_{\text{DC,string}}} \cdot \frac{1}{N_{\text{string,structure}}}\right) \cdot N_{\text{strings,structure}} \tag{2.2}$$

Where:

- $N_{\text{strings,area}}$ is the number of strings to install in the area evaluated.
- $P_{\text{AC,comb}}$ is the active AC power related to the combination of power stations installed in the area.
- $R_{\text{DC/AC, desired}}$ is the desired DC/AC ratio.
- $P_{\text{DC,string}}$ is the DC power related to one string.
- $N_{\text{strings,structure}}$ is the number of strings installed in one structure.

2.2.2 Maximum capacity installing the maximum peak power

This option ensures that the maximum AC power is installed, installing the maximum DC power in every area, not exceeding the limits of DC/AC ratio ± 0.15.

Many combinations are evaluated, following the procedure explained hereafter.

For every possible power station, starting with the default one and following with the non-default ones sorted by AC power, the lower and upper amount of power stations of each type that can be installed is calculated using Equation 2.3 and Equation 2.4.

$$N_{\text{PS,lower}} = Floor\left(\frac{P_{\text{DC,available}}}{P_{\text{AC,PS}} \cdot R_{\text{DC/AC, desired}} + P_{\text{DC,embedded}}}\right) \tag{2.3}$$

$$N_{\text{PS,upper}} = Ceil\left(\frac{P_{\text{DC,available}}}{P_{\text{AC,PS}} \cdot R_{\text{DC/AC, desired}} + P_{\text{DC,embedded}}}\right) \tag{2.4}$$

Where:

- $N_{\text{PS,upper}}$ is the upper amount of the power station in evaluation to install. When installing this amount of the power station in evaluation, there cannot be other power stations installed afterwards, as would give a DC/AC ratio that deviates more from the one desired.
- $N_{\text{PS,lower}}$ is the lower amount of the power station in evaluation to install. When installing this amount of the power station in evaluation, there can be other power stations installed afterwards.
- $P_{\text{DC,available}}$ is the DC power available. It is recalculated considering the lower number of previous power stations already installed.
- $P_{\text{AC,PS}}$ is the active AC power of the power station in evaluation.
- $R_{\text{DC/AC, desired}}$ is the desired DC/AC ratio.
- $P_{\text{DC,embedded}}$ is the DC power loss relative to one embed power station (if applicable).

For every possible combination, it will be evaluated if installing the maximum number of strings available would give a DC/AC ratio within the limits. If so, that number of strings will be considered as the maximum that can be installed with that combination. If not, the maximum number of strings that can be installed for the combination in evaluation is calculated as the value that would give the maximum possible DC/AC ratio.

From all the combinations in consideration, the resulting combination for the area in evaluation is the one with the highest DC power and the DC/AC ratio closest to the one desired.

2.2.3 Specific capacity

This option ensures that the required AC power is installed, while also getting the DC/AC ratio defined by the user.

It is important to note that, with this option, the areas that will be filled first with the inverters defined will be the ones that are closest to the substation.

To calculate the resulting combination of power stations, a similar approach to the one explained above for maximum capacity is followed, but considering also the number of inverters that are remaining to be installed.

For every possible power station, starting with the default one and following with the non-default ones sorted by AC power, the number of power stations installed is calculated using Equation 2.5.

$$N_{\text{PS}} = Min\left(N_{\text{remaining,PS}}, N_{\text{max,PS}}\right) \tag{2.5}$$

Where:

- $N_{\text{remaining,PS}}$ is the number of power stations that can be installed according to the inverters remaining to be installed. It is calculated as the minimum relation between the inverters remaining and the ones defined in the power station in evaluation.
- $N_{\text{max,PS}}$ is the maximum number of power stations that can be installed according to the DC power available, calculated using Equation 2.6.

$$N_{\text{max, PS}} = Floor\left(\frac{P_{\text{DC,available}}}{P_{\text{AC,PS}} \cdot R_{\text{DC/AC, desired}} + P_{\text{DC,embedded}}}\right) \tag{2.6}$$

And:

- $N_{\text{max,PS}}$ is the maximum amount of the power station in evaluation.
- $P_{\text{DC,available}}$ is the DC power available. It is recalculated considering the lower number of previous power stations already installed.
- $P_{\text{AC,PS}}$ is the active AC power of the power station in evaluation.
- $R_{\text{DC/AC, desired}}$ is the desired DC/AC ratio.
- $P_{\text{DC,embedded}}$ is the DC power loss relative to one embed power station (if applicable).

The total number of strings installed is calculated by Equation 2.2.

2.2.4 Distribution of strings into inverters

The objective is to minimise the number of inverters working at different DC/AC ratios, while having the power stations as balanced as possible.

For each inverter, the optimal number of strings to get the DC/AC ratio closest to the resulting one is using Equation 2.7.

$$N_{\text{strings,inverter}} = Round\left(\frac{P_{\text{AC,inverter}} \cdot R_{\text{DC/AC, resulting}}}{P_{\text{DC,string}}} \cdot \frac{1}{N_{\text{string,structure}}}\right) \cdot N_{\text{strings,structure}} \tag{2.7}$$

Where:

- $N_{\text{strings,inverter}}$ is the number of strings installed in the inverter evaluated.
- $P_{\text{AC,inverter}}$ is the active AC power related to the inverter evaluated.
- $R_{\text{DC/AC, resulting}}$ is the resulting DC/AC ratio.
- $P_{\text{DC,string}}$ is the DC power related to one string.
- $N_{\text{strings,structure}}$ is the number of strings installed in one structure.

This number of strings defined per inverter could imply exceeding or not reaching the number of strings desired to be installed in the area. The number of strings remaining to be installed or removed from defined inverters is calculated as byEquation 2.8.

$$N_{\text{strings, redistribution}} = N_{\text{strings, area}} - \sum_{i=1}^{N_{\text{inv, area}}} N_{\text{strings, i}} \tag{2.8}$$

Where:

- $N_{\text{strings,redistribution}}$ is the number of strings that are remaining to be installed or that have to be removed from defined inverters. Note that this value can be negative or positive.
- $N_{\text{strings,area}}$ is the number of strings to be installed in the area.
- $N_{\text{inv,area}}$ is the number of inverters defined in the area.
- $N_{\text{strings,i}}$ is the number of strings installed in the inverter in evaluation.

These strings remaining to be installed imply a certain number of inverters to be redistributed, calculated using Equation 2.9.

$$N_{\text{inverters, adapt}} = \frac{Abs(N_{\text{strings, redistribution}})}{N_{\text{strings, structure}}} \tag{2.9}$$

Where:

- $N_{\text{inverters,adapt}}$ is the number of inverters to be adapted in the area.
- $N_{\text{strings,redistribution}}$ is the number of strings that are remaining to be installed or that have to be removed from defined inverters. Note that this value can be negative or positive.
- $N_{\text{strings,structure}}$ is the number of strings installed in one structure.

The number of inverters to be redistributed per power station will be directly related to the total contribution of its inverters to the total number of inverters.

$$N_{\text{inverters, adapt PS}} = \frac{N_{\text{inverters, PS}}}{N_{\text{inverters, total}}} \cdot N_{\text{inverters, adapt}} \tag{2.10}$$

Where:

- $N_{\text{inverters,adapt PS}}$ is the number of inverters to adapt in the PS.
- $N_{\text{inverters,PS}}$ is the total number of inverters that compose the PS.
- $N_{\text{inverters, total}}$ is the total number of inverters installed in the area.
- $N_{\text{inverters,adapt}}$ is the number of inverters to be adapted in the area.

Lastly, the inverters that will be adapted to include the strings remaining will be the ones with higher AC power, as those will have a lower deviation on the DC/AC ratio.

Chapter 3

Electrical Sizing Criteria

This section explains the different criteria followed by each of the electrical standards that pvDesign offers.

3.1 Introduction

To size the cables of the PV plant based on the electrical standards, the following criteria must be satisfied:

- Current-carrying capacity criterion: The operating current is corrected based on the different characteristics of the installation and the site. This corrected value must then be lower than the maximum current-carrying capacity that the cable can withstand. These maximum current-carrying capacity values are based on standard tables.
- Short-circuit temperature rise criterion: The short-circuit current must be lower than the limit supported by the cabling. This criterion is taking into account only for medium voltage cables.
- Voltage drop criterion: The voltage drop criterion which states that the voltage drop in each cable should be lower than the maximum values established by the user in pvDesign. Although this criterion is considered to size the cable, to not comply with this condition do not imply that the cable becomes damaged, but imply that the losses will be higher.

The constraints considered when calculating the low voltage (LV) and medium voltage (MV) cables were:

- To minimize the costs using the minimum valid cable cross-section(s). We tend to limit the number of cross-sections to a maximum of two in each sub-system of the PV plant (standardize the cable cross-sections).
- Copper is proposed as the conducting material for the LV DC string cables. Aluminium is proposed as the conducting material for the rest of cables (DC, AC and MV).

The assumptions made when sizing and rating the cables are the following:

- The soil temperature equals 25°C if no information is available.

- The ambient temperature is the maximum historical temperature of the site (provided by the meteo data source).
- The soil resistivity equals 1 K·m/W if no information is available.
- The depth of cables are 700 mm for buried LV cables and 900 mm for MV cables.
- There is no space between LV cables and the MV cables are spaced 0.2 m between group centres.
- String cables are fastened to the structures. The rest of LV cables are directly buried in trenches. MV radial networks from the power stations to the substation are directly buried in trenches.

3.2 Cable selection based on the maximum current-carrying capacity

The current-carrying capacity is defined as the maximum current that can flow through an electric conductor without damaging it. This value varies depending on the conductor, environmental conditions, cross-section, insulating material, the number of grouped conductors, among others.

The operating current is corrected based on the different characteristics of the installation and the site. This corrected value must then be lower than the maximum current-carrying capacity that the cable can withstand.

The equation for the corrected allowed current is given by Equation 3.1.

$$\boxed{I_{\text{sizing}} \leq I_{\text{ccc}}} \tag{3.1}$$

Where:

- I_{sizing} is the sizing current for the current-carrying capacity criterion in [A].
- I_{ccc} are the current values standardized for each cable cross-section based on the cable and the installation characteristics in [A]

As it is presented in the following sections, the operating current of the cable is corrected with some factors:

1. An ambient air temperature correction factor is only applied when the cables are exposed to air or installed in trays fastened to the structures.
2. A soil temperature correction factor is only applied when the cables are directly buried in trenches or underground cable ducts.
3. A soil resistivity correction factor is only applied when the cables are directly buried in trenches or underground cable ducts.
4. We consider a depth of burial correction factor is only applied when the cables are directly buried in trenches or underground cable ducts.
5. Grouping cables together leads to additional heating of the cables which increases the current passing through them.

3.2.1 IEC standard

Based on IEC standards [1] and [2], the sizing current is given by Equation 3.2.

$$I_{\text{sizing}} = \frac{I_{\text{operating}}}{CF} \tag{3.2}$$

Where:

- I_{sizing} is the sizing current for the current-carrying capacity criterion in [A].
- $I_{\text{operating}}$ is the load current running through the cable in [A].
- CF is the product of all the applied correction factors.

The ambient and soil temperature correction factors are calculated using Equation 3.3.

$$CF_{\text{temp}} = \left[\frac{\theta_{\text{i}} - \theta_{\text{a}}}{\theta'_{\text{i}} - \theta'_{\text{a}}} \cdot \frac{\beta + \theta'_{\text{i}}}{\beta + \theta_{\text{i}}} \right]^{\frac{1}{2}} \tag{3.3}$$

Where:

- CF_{temp} is the ambient or soil temperature correction factor.
- β is the reciprocal of the temperature coefficient of resistivity at 0°C. This parameter equals 234.5 °C for copper (Cu) and 228 °C for aluminium (Al).
- θ'_{i} is the conductor rated temperature at which the base ampacity is specified in [°C].
- θ_{i} is the maximum allowable conductor temperature in [°C]. It equals the maximum operational insulator temperature in normal operation.
- θ'_{a} is the ambient or soil temperature at which the base ampacity is specified in [°C].
- θ_{a} is the actual soil or ambient temperature in [°C]. It equals the maximum historical air temperature of the site or a temperature of 25 °C underground cables.

The other correction factors that are used to size a cable according to IEC standards are given in Table 3.1.

Table 3.1: The correction factors that are considered to size a cable according to IEC standards, [1] and [2].

Correction Factors	For MV cables: IEC 60502-2	For LV cables: IEC 60364-5-52
For soil thermal resistivities	Table B.14, B.15, B.16, and B.17	Table B.52.16
For depths of laying	Table B.12 and B.13	Not applied
For groups of cables	Table B.18, B.19, B.20, B.21, B.22, and B.23	Table B.52.17, B.52.18, B.52.19

According to IEC standards [1] and [2], in order to compute the correction factor for a group of cables:

- For DC cables: Two single-core cables or one multi-core cable are considered as one current-carrying conductor.

- For AC cables: Three single-core cables or one multi-core cable are considered as one current-carrying conductor.

3.2.2 NEC standard

Based on the Article 690 of the NEC standard [3], the sizing current for the output circuit of a PV plant (from inverters to the substation) is given by Equation 3.4.

$$I_{\text{sizing}} = \frac{I_{\text{operating}}}{CF} \tag{3.4}$$

Where:

- I_{sizing} is the sizing current for the current-carrying capacity criterion in [A].
- $I_{\text{operating}}$ is the load current running through the cable in [A]. It is the inverter continuous output current for string inverters and the operating current for the MV system.
- CF is the product of all the applied correction factors.

The sizing current for the photovoltaic source circuit (from modules to the inverters) is given by Equation 3.5.

$$I_{\text{sizing}} = max\left(I_{\text{corrected}}\,,\ I_{\text{OCPD}}\right) \tag{3.5}$$

Where $I_{\text{corrected}}$ is calculated using Equation 3.6.

$$I_{\text{corrected}} = \frac{1.25 \cdot I_{\text{sc}}}{CF} \tag{3.6}$$

Where:

- $I_{\text{corrected}}$ is the current corrected by factors in [A].
- I_{sc} is the short-circuit current of the PV module for the string cables and the short-circuit current of the module multiplied by the number of strings per box/DC bus in [A].
- CF is the product of all the applied correction factors.

And the I_{OCPD} is calculated by Equation 3.7.

$$1.25 \cdot (1.25 \cdot I_{\text{sc}}) = 1.56 \cdot I_{\text{sc}} \Rightarrow I_{\text{OCPD}} \tag{3.7}$$

After that, we raise the result to the next standard fuse or circuit breaker size defined in section 240.6 of the NEC. The obtained current will be denoted as I_{OCPD}.

Where:

- I_{OCPD} is the protective device rated current defined in section 240.6 of the NEC in [A].
- I_{sc} is the short-circuit current of the PV module for the string cables and the short-circuit current of the module multiplied by the number of strings per box/DC bus in [A].

The ambient and soil temperature correction factors are calculated using Equation 3.3. The other correction factors that are used to size a cable according to NEC standards are given in Table 3.2.

Table 3.2: The correction factors that are considered to size a cable according to NEC standard [3]

Correction Factors	For MV and LV cables: NEC 2017
For soil thermal resistivities	IEEE Std 399-1997 Table 13-5, 13-6, 13-7
For depths of laying	NEC Annex B, Section B.3(b)
For groups of cables	NEC Annex B, Table B.310.15(B)(2)(11)

According to NEC standards, in order to compute the correction factor for a group of cables:

- For DC cables: Two single-core cables or one multi-core cable are considered as two current-carrying conductors.
- For AC cables: Three single-core cables or one multi-core cable are considered as three current-carrying conductors.

3.2.3 Temperature of the cable

The temperature of the cable is calculated using Equation 3.8. [4]

$$\theta = \theta_{\mathrm{amb}} + (\theta_{\mathrm{i}} - \theta_{\mathrm{amb}}) \cdot \left(\frac{I}{I_{\mathrm{a}}}\right)^2 \tag{3.8}$$

Where:

- θ is the temperature of the cable in [°C].
- θ_{amb} is the ambient/ground temperature in [°C].
- θ_{i} is the maximum allowable conductor temperature in [°C]. It equals the maximum operational insulator temperature in normal operation.
- I is the load current in [A].
- I_{a} is current-carrying capacity for the conductor based on standard tables in [A].

3.3 Cable selection based on short-circuit temperature rise

When a short-circuit occurs, the amount of current flowing through the conductor might surpass nominal current during short periods of time, heating up the insulator. It is necessary to verify that the proposed cross-section can withstand the maximum short-circuit current. This criterion is only applied in the case of MV cables and the equation that is applied is valid for all the electrical standards. [5]

The cross-section of the cable is given by Equation 3.9.

$$S = \frac{I_{\mathrm{AD}} \cdot \sqrt{t}}{k} = \frac{I_{\mathrm{sc}} \cdot \sqrt{t}}{\varepsilon \cdot k} \tag{3.9}$$

Where:

- S the cable cross-section in $[mm^2]$.
- I_{AD} is the short-circuit current for adiabatic conditions.
- I_{sc} is the short-circuit current. The complete calculation of this short-circuit current is presented in [6].
- ε is the cable heat dissipation factor. For adiabatic conditions $\varepsilon = 1$.
- t is the short-circuit duration in [s]. It equals 1 [s].
- k is given by Equation 3.10.

$$k = K \cdot \sqrt{ln\left(\frac{\theta_{\mathrm{f}} + \beta}{\theta_{\mathrm{i}} + \beta}\right)} \tag{3.10}$$

Where:

- K is a constant that depends on the nature of the conductor and the temperature limit of the insulator in $[As^{0.5}/m^2]$. This parameter equals $226\, As^{0.5}/mm^2$ for copper (Cu) and $148\, As^{0.5}/mm^2$ for aluminium (Al).
- β is the reciprocal of the temperature coefficient of resistivity at 0°C. This parameter equals 234.5 °C for copper (Cu) and 228 °C for aluminium (Al).
- θ_{f} is the final short circuit temperature of the conductor in [°C]. Its value depends on the standard.
- θ_{i} is the maximum allowable conductor temperature in [°C]. It equals the maximum operational insulator temperature in normal operation.

Hence, the cross-section of the cable is given by Equation 3.11.

$$\boxed{S = \frac{I_{\mathrm{sc}} \cdot \sqrt{t}}{K \cdot \sqrt{ln\left(\frac{\theta_{\mathrm{f}} + \beta}{\theta_{\mathrm{i}} + \beta}\right)}}} \tag{3.11}$$

Where the K that is a constant that depends on the nature of the conductor and the temperature limit of the insulator and β that is the reciprocal of the temperature coefficient of resistivity at 0°C, are shown in Table 3.3.

Table 3.3: Constants that depend on the nature of the conductor

Conductor material	K $[As^{0.5}/m^2]$	β [°C]
Copper	226	234.5
Aluminium	148	228

3.3.1 IEC standard

The IEC standard that has been followed to perform this calculation is [1] and [2]. In addition, the IEC 60502-2 presents the maximum conductor temperatures for different types of insulating compound and they can be seen in Table 3.4.

Table 3.4: Maximum conductor temperatures for different types of insulating compound according to IEC [1] and [2].

Maximum conductor temperature [°C]	XLPE	EPR
in normal operation, θ_i	90	90
in short-circuit conditions, θ_f	250	250

3.3.2 NEC standard

According to Table 240.92(B) in [3], conductors are considered to be protected under short-circuit conditions when their short-circuit temperature limit is not exceeded. Conductor heating under short-circuit conditions is determined by Equation 3.12 or Equation 3.13.

$$I_{sc}^2 \cdot t = 0.0297 \cdot S_{\mathrm{Cu}}^2 \cdot log_{10}\left(\frac{\theta_\mathrm{f} + 234.5}{\theta_\mathrm{i} + 234.5}\right) \tag{3.12}$$

$$I_{sc}^2 \cdot t = 0.0125 \cdot S_{\mathrm{Al}}^2 \cdot log_{10}\left(\frac{\theta_\mathrm{f} + 228}{\theta_\mathrm{i} + 228}\right) \tag{3.13}$$

Where:

- S the cable cross-section in [cmils].
- I_{sc} the maximum short-circuit current in [A].
- θ_f is the final short circuit temperature of the conductor in [°C]. Its value depends on the standard.
- θ_i is the initial short circuit temperature of the conductor in [°C]. Its value depends on the standard.
- t is the short-circuit duration in [s]. It equals 1 seconds.

However, by applying Equation 3.14 and Equation 3.15.

$$log_{10}(x) = \frac{ln(x)}{2.3} \tag{3.14}$$

$$1\,mm^2 = 1973.5\,cmil \tag{3.15}$$

The NEC equations to calculate the section based on the short-circuit rise criterion are the same as the method followed by the IEC.

$$S_{\mathrm{Cu}} = \frac{I_{sc} \cdot \sqrt{t}}{\sqrt{\frac{0.0297}{2.3}} \cdot 1973.5 \cdot \sqrt{ln\left(\frac{\theta_\mathrm{f} + 234}{\theta_\mathrm{i} + 234}\right)}} \Rightarrow K_{\mathrm{Cu}} = 224.1 \approx 226\,As^{0.5}/mm^2 \tag{3.16}$$

$$S_{\mathrm{Al}} = \frac{I_{\mathrm{sc}} \cdot \sqrt{t}}{\sqrt{\frac{0.0125}{2.3}} \cdot 1973.5 \cdot \sqrt{ln\left(\frac{\theta_{\mathrm{f}}+228}{\theta_{\mathrm{i}}+228}\right)}} \Rightarrow K_{\mathrm{Al}} = 145.4 \approx 148\, As^{0.5}/mm^2 \tag{3.17}$$

The NEC presents the maximum conductor temperatures for different types of insulating compound and they can be seen in Table 3.5.

Table 3.5: Maximum conductor temperatures for different types of insulating compound according to NEC [3].

Maximum conductor temperature [°C]	THHN	XHHN
in normal operation , θ_{i}	75	90
in short-circuit conditions, θ_{f}	150	250

3.3.3 Consequences of taking the cable heat dissipation factor = 1

According to [7], the cable heat dissipation factor is given by Equation 3.18.

$$\varepsilon = \sqrt{1 + F \cdot A \cdot \sqrt{\frac{t}{S}} + F^2 \cdot B \cdot \left(\frac{t}{S}\right)} \tag{3.18}$$

Where:

- ε is the cable heat dissipation factor.
- F is a factor that considers the irregularity of the thermal contacts between conductors. It equals to 0.7.
- S the cable cross-section in $[mm^2]$.
- t is the short-circuit duration in [s]. It equals 1 seconds.
- A, B are empirical constants.

In order to analyse the error that is made by estimating a dissipation factor equals to 1, the next process has been followed.

1. The cross-section of the cable is calculated with a dissipation factor equals to 1.
2. Then, the cross-section is introduced in Equation 3.18 and the real dissipation factor is obtained.
3. If the real dissipation factor is closed to 1, the error made would be negligible.

As presented in Figure 3.1 and Figure 3.2, the real dissipation factor for short-circuit currents higher than 10 kA (more common short-circuit currents for the MV system of a PV plant), is almost 1. In conclusion, the dissipation factor can be taken as 1 and the error made would be negligible.

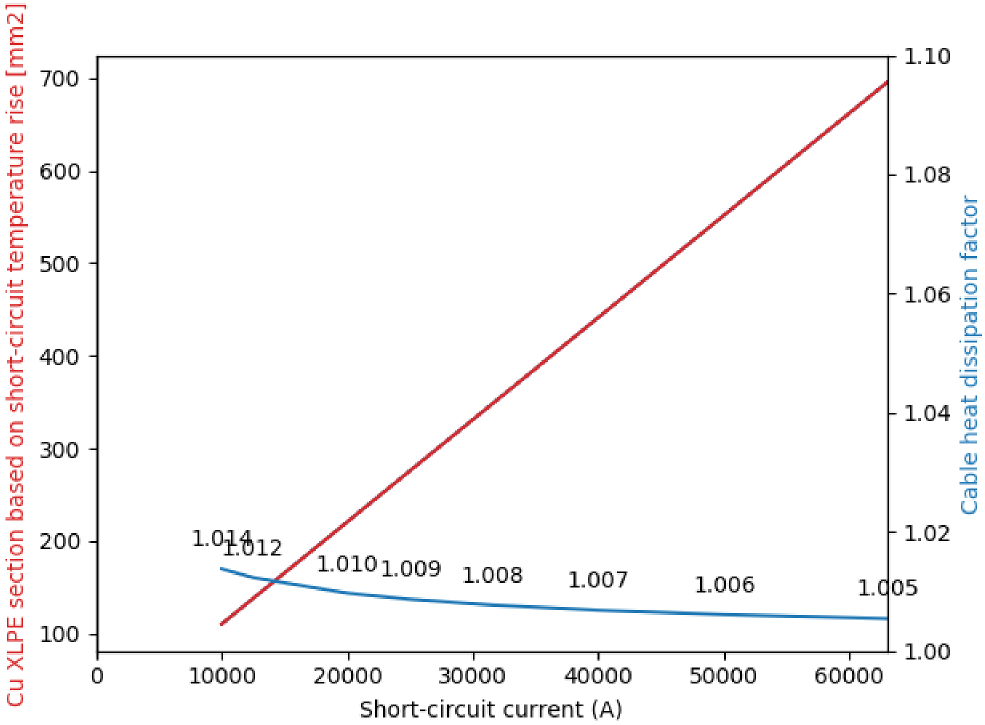


Figure 3.1: Dissipation factor and Cu XLPE cross-section based on short-circuit temperature rise $[mm^2]$. Source: Own elaboration.

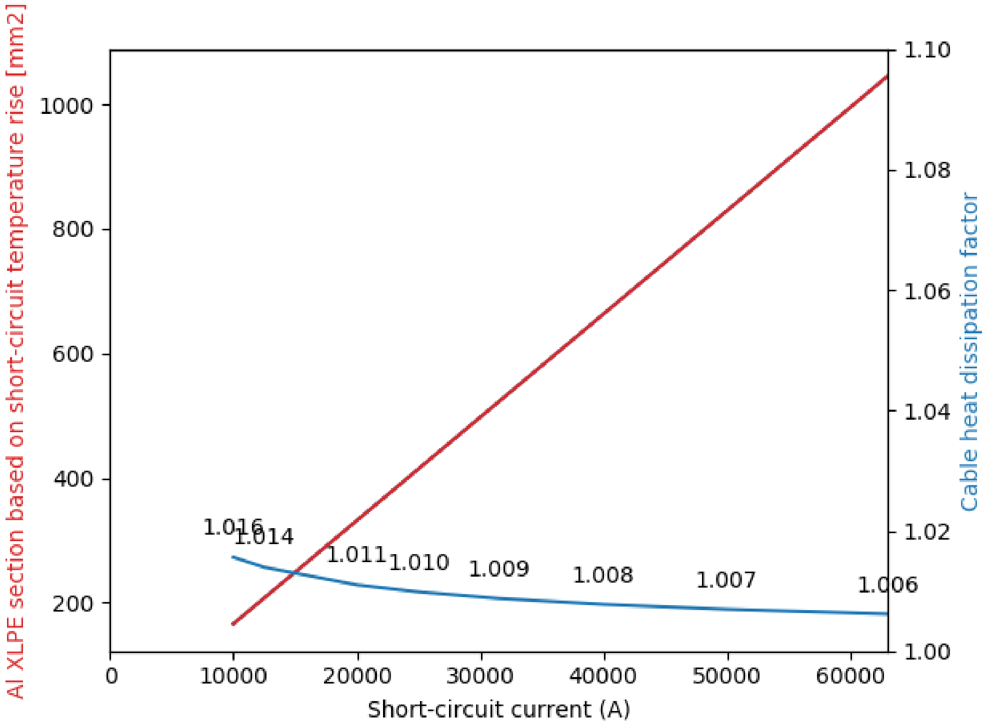


Figure 3.2: Dissipation factor and Al XLPE cross-section based on short-circuit temperature rise $[mm^2]$. Source: Own elaboration.

3.4 Cable selection based on voltage drop

Voltage drop limitations impose the use of bigger cable cross-sections. However, not to fulfil with this criterion only derives in higher losses. To calculate the cable cross-section that respects the voltage drop limit chosen by the user the following equations are used. These equations vary slightly depending on the type of current running through the cable.

In the case of AC cables, in both LV and MV sub-systems, the minimum cable cross-section per the voltage drop criterion ig given by Equation 3.19.

$$\boxed{S = \frac{\sqrt{3} \cdot \rho \cdot L \cdot I}{\Delta V \cdot V}} \tag{3.19}$$

Where:

- S the cable cross-section in $[mm^2]$.
- ρ is the conducting material resistivity at the cable's insulator maximum operational temperature in $[\Omega m^2/m]$.
- L is the cable length in [m].
- I is the operating current running through the cable in [A].
- ΔV is the voltage drop in parts per one.
- V is the voltage of the system of the PV plant in [V].

In the case of DC cables, the minimum cable cross-section per the voltage drop criterion ig given by Equation 3.20.

$$\boxed{S = \frac{2 \cdot \rho \cdot L \cdot I}{\Delta V \cdot V}} \tag{3.20}$$

Where:

- S the cable cross-section in $[mm^2]$.
- ρ is the conducting material resistivity at the cable's insulator maximum operational temperature in $[\Omega m^2/m\ ]$.
- L is the cable length in [m].
- I is the operating current running through the cable in [A].
- ΔV is the voltage drop in parts per one.
- V is the voltage of the system of the PV plant in [V].

The resistivity of the conducting material at a specific temperature is calculated using Equation 3.21.

$$\rho(\theta_\mathrm{i}) = \rho(20^\circ C) \cdot (1 + \alpha(\theta_\mathrm{i} - 20)) \tag{3.21}$$

Where:

- ρ is the conducting material resistivity at the cable's insulator maximum operational temperature in $[\Omega m^2/m]$.
- $\rho(20°C)$ is the conducting material resistivity at 20°C in $[\Omega m^2/m]$. It equals $1/56 \cdot 10^{-6}\ \Omega m^2/m$ for copper and $1/35 \cdot 10^{-6}\ \Omega m^2/m$ for aluminium
- α is a parameter that depends on the type of material used. It equals $0.00392\ °C^{-1}$ for copper and $0.00403\ °C^{-1}$ for aluminium.
- θ_{i} is the maximum allowable conductor temperature in [°C]. It equals the maximum operational insulator temperature in normal operation.

3.4.1 Consequences of taking the maximum operational temperature of the insulation for cable sizing based on voltage drop

To size the cable based on the voltage drop criterion, the temperature that has been taken to obtain the section equals the maximum operation temperature of the insulation material in normal conditions. These temperatures can be seen in Table 3.6.

Table 3.6: Maximum conductor temperatures for different types of insulating in normal condition to electrical standards

Maximum conductor temperature [°C]	PVC	THHN	EPR/XLPE/XHHN
in normal operation , θ_{i}	70	75	90

Sometimes, this temperature is taken as the maximum ambient temperature: 30 °C or 35 °C. This decision can cause up to 25% error when sizing a cable. Taking the maximum operational temperature causes more conservative results as it is seen in Figure 3.3.

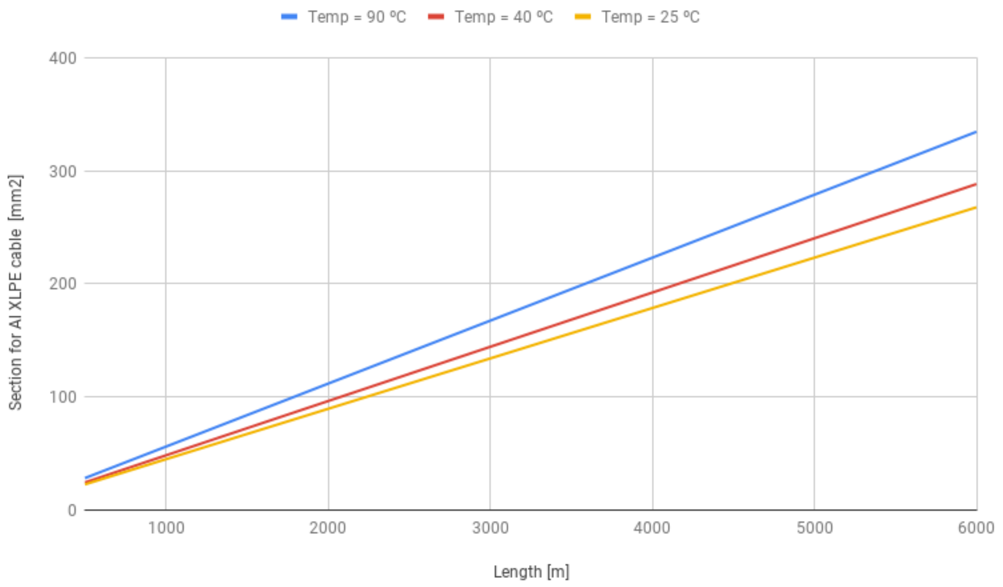


Figure 3.3: Al XLPE cable cross-section based on resistivities at different temperatures $[mm^2]$. Source: Own elaboration.

3.4.2 Consequences of taking the AC resistance equals to the DC resistance

There is a slight difference between the DC cable resistance and the AC cable resistance. The second one is affected by the skin effect and the proximity of other conductors. The AC resistance is calculated using Equation 3.22. [7]

$$R_{\mathrm{AC}} = R_{\mathrm{DC}} \cdot (1 + y_{\mathrm{s}} + y_{\mathrm{p}}) \tag{3.22}$$

Where:

- R_{AC} is the AC cable resistance Ω/m.
- R_{DC} is the DC cable resistance Ω/m.
- y_{s} represents the skin effect.
- y_{s} represents how other close conductors affect the cable.

Considering the DC cable resistance equals to the AC cable resistance can produce a maximum of 7% error for sections from 300 to 630 mm^2. For sections lower than 300 mm^2, this error is negligible. Taking both resistances as equals causes less conservative results as it is seen in Figure 3.4 and Figure 3.5.

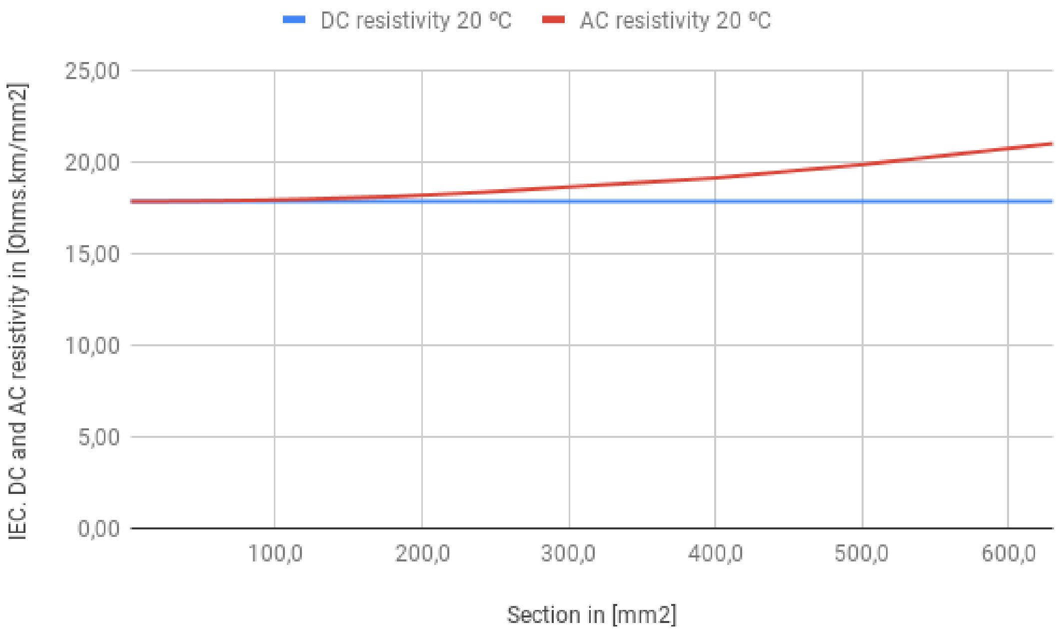


Figure 3.4: AC and DC resistivities for a Cu cable based on IEC. Source: Own elaboration.

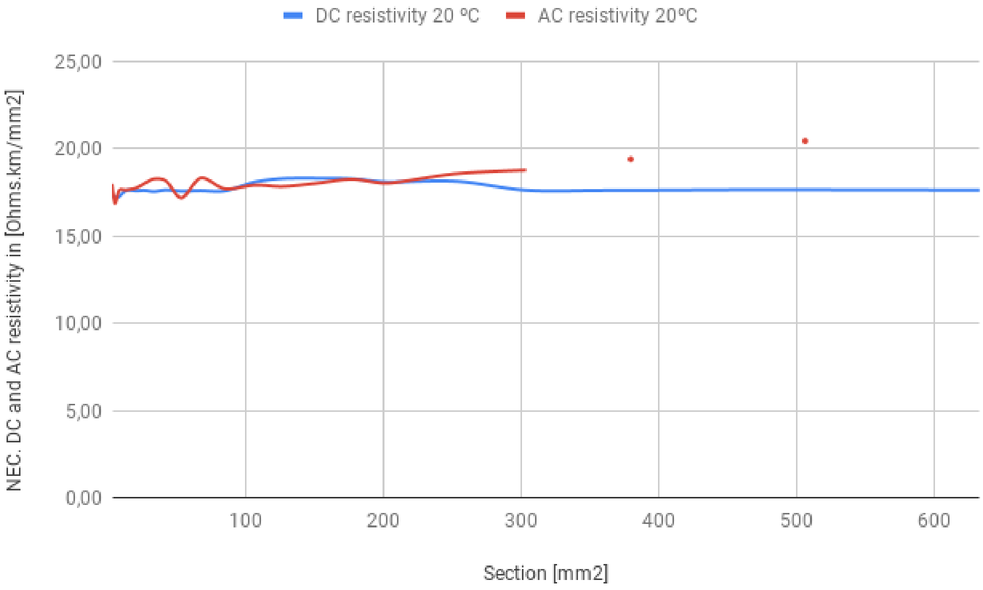


Figure 3.5: AC and DC resistivities for a Cu cable based on Tables 8 and 9 of the NEC standard. Source: Own elaboration.

3.4.3 Consequences of not considering the reactive power

The formula to calculate the cross-section of a cable taking into account the reactance in a AC system is given by Equation 3.23.

$$S = \frac{\sqrt{3} \cdot \rho \cdot L \cdot I \cdot cos\varphi}{\Delta V - \sqrt{3} \cdot x/n \cdot L \cdot I \cdot sin\varphi} \tag{3.23}$$

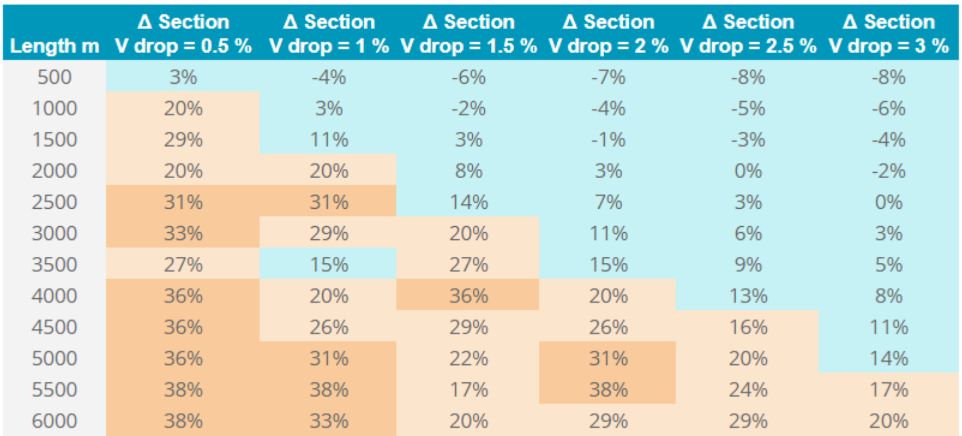
Where:

- S the cable cross-section in $[mm^2]$.
- L is the cable length in [m].
- I is the operating current running through the cable in [A].
- ΔV is the voltage drop in parts per one.
- ρ is the conducting material resistivity at the cable's insulator maximum operational temperature in $[\Omega m^2/m\ ]$.
- x is the reactance of the cable in $[\Omega/m]$.
- n is the number of conductor per phase.

At this moment, pvDesign is not able to size the cable using the cosine of phi. For that reason, a study about how the reactance of the line will affect the selection of the cross-section of Al and Cu cables has been performed. A reactance of $0.08\ \Omega/km$ has been selected.

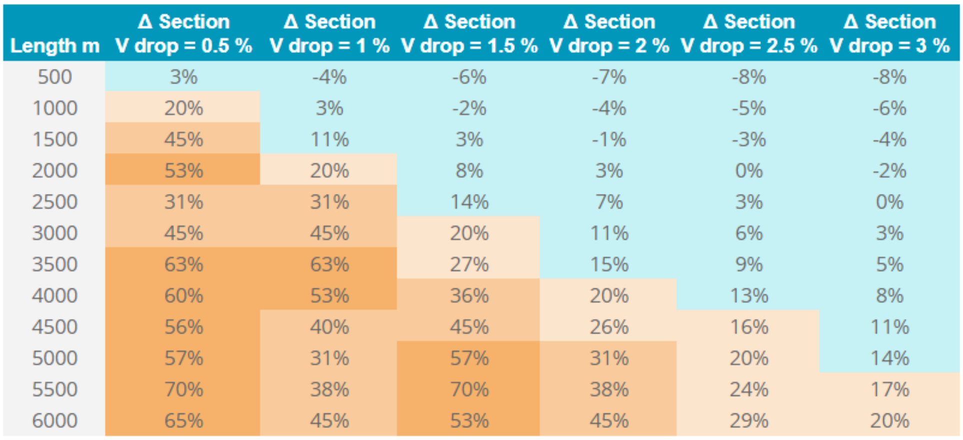
In Figure 3.6 and Figure 3.7, the results that have been presented show the increase of section that would be necessary if the reactance of the line is considered in comparison with the sections obtained using Equation 3.19.

Hence, it is recommended to rise the allowed voltage drop for MV lines as the PV plant surface increase in order to have more realistic cross-sections. In conclusion, not taking into account the reactance of the line implies less conservative results.



Length m	Δ Section V drop = 0.5 %	Δ Section V drop = 1 %	Δ Section V drop = 1.5 %	Δ Section V drop = 2 %	Δ Section V drop = 2.5 %	Δ Section V drop = 3 %
500	3%	-4%	-6%	-7%	-8%	-8%
1000	20%	3%	-2%	-4%	-5%	-6%
1500	29%	11%	3%	-1%	-3%	-4%
2000	20%	20%	8%	3%	0%	-2%
2500	31%	31%	14%	7%	3%	0%
3000	33%	29%	20%	11%	6%	3%
3500	27%	15%	27%	15%	9%	5%
4000	36%	20%	36%	20%	13%	8%
4500	36%	26%	29%	26%	16%	11%
5000	36%	31%	22%	31%	20%	14%
5500	38%	38%	17%	38%	24%	17%
6000	38%	33%	20%	29%	29%	20%

Figure 3.6: Average increase of cross-sections for Al cables considering different voltage drops for cos phi = 0.95, 0.9 and 0.85, and different cable lengths. Source: Own elaboration



Length m	Δ Section V drop = 0.5 %	Δ Section V drop = 1 %	Δ Section V drop = 1.5 %	Δ Section V drop = 2 %	Δ Section V drop = 2.5 %	Δ Section V drop = 3 %
500	3%	-4%	-6%	-7%	-8%	-8%
1000	20%	3%	-2%	-4%	-5%	-6%
1500	45%	11%	3%	-1%	-3%	-4%
2000	53%	20%	8%	3%	0%	-2%
2500	31%	31%	14%	7%	3%	0%
3000	45%	45%	20%	11%	6%	3%
3500	63%	63%	27%	15%	9%	5%
4000	60%	53%	36%	20%	13%	8%
4500	56%	40%	45%	26%	16%	11%
5000	57%	31%	57%	31%	20%	14%
5500	70%	38%	70%	38%	24%	17%
6000	65%	45%	53%	45%	29%	20%

Figure 3.7: Average increase of cross-sections for Cu cables considering different voltage drops for cos phi = 0.95, 0.9 and 0.85, and different cable lengths. Source: Own elaboration

Bibliography

[1] Technical Committee 20, “Power cables with extruded insulation and their accessories for rated voltages from 1 kv (um = 1,2 kv) up to 30 kv (um = 36 kv) - part 2: Cables for rated voltages from 6 kv (um = 7,2 kv) up to 30 kv (um = 36 kv),” International Electrotechnical Commision, IEC 60502-2:2014, 2014.

[2] Technical Committee 64, “Low-voltage electrical installations - part 5-52: Selection and erection of electrical equipment - wiring systems,” International Electrotechnical Commision, IEC 60364-5-52:2009, 2009.

[3] National Electrical Code Committee, “Nfpa 70 national electrical code,” International Standard, 2017.

[4] Prysmian Group, “Manual tecnico y practico de cables y accesorios para media tension,” White paper, 2008.

[5] Technical Committee 20, “Calculation of thermally permissible short-circuit currents, taking into account non-adiabatic heating effects,” International Electrotechnical Commision, IEC 60949:1988, 1988.

[6] RatedPower, “Substation methodology. a methodology to design an air-insulated substation,” RatedPower, 2020.

[7] Technical Committee 20, “Electric cables - calculation of the current rating - part 1-1: Current rating equations and calculation of losses - general,” International Electrotechnical Commision, IEC 60287-1-1:2006, 2006.

[8] Technical Committee 84, “Photovoltaic (pv) arrays - design requirements,” International Electrotechnical Commision, IEC 62548:2016, 2016.

[9] Technical Committee 82, “Ground-mounted photovoltaic power plants - design guidelines and recommendations,” International Electrotechnical Commision, IEC TS 62738:2018, 2018.

[10] IEEE, “IEEE Recommended Practice for Industrial and Commercial Power Systems Analysis,” no. IEEE Std 399-1997, 1997.

[11] Technical Committee 20, “Electric cables - calculation of the current rating - part 3-1: Operating conditions - site reference conditions,” International Electrotechnical Commision, IEC 60287-3-1:2017, 2017.

[12] Technical Committee 64, “Low-voltage electrical installations - part 5-54: Selection and erection of electrical equipment - earthing arrangements and protective conductors,” International Electrotechnical Commision, IEC 60364-5-54:2011, 2006.

Appendix A

Determining the distribution of strings

For a better understanding of the process followed by pvDesign to calculate the distribution of strings into inverters and power stations, one case scenario with the following characteristics is considered:

1. There is just one available area.
2. The PV module has a DC power of 595 W.
3. The central inverter has an AC power of 2500 kVA.
4. The structure is a 2V tracker with 3 strings, each of which has a total number of 25 modules. The maximum number of structures that can be installed is 743.
5. The default power station has 2 inverters and is located outside the DC field.
6. The objective is to install the maximum capacity while installing the maximum peak power, with an objective DC/AC ratio of 1.2.

The possible power stations to be defined are:

1. Default power station: formed by 2 central inverters.
2. Non-default power station: formed by 1 central inverter.

The maximum DC power available is calculated as:

$$P_{\text{DC,available}} = 0.595\,kWdc/mod \cdot 25\,mods/string \cdot 2229\,strings = 33156.375\,kWdc \tag{A.1}$$

The lower and upper number of default power stations that can be installed is calculated as:

$$N_{\text{defPS,lower}} = Floor\left(\frac{P_{\text{DC,available}}}{P_{\text{AC,PS}} \cdot R_{\text{DC/AC, desired}} + P_{\text{DC,embedded}}}\right) \tag{A.2}$$

$$N_{\text{defPS,lower}} = \mathit{Floor}\left(\frac{33156.375\,kWdc}{5000\,kWac \cdot 1.2\dfrac{kWdc}{kWac} + 0}\right) = 5 \tag{A.3}$$

$$N_{\text{defPS,upper}} = \mathit{Ceil}\left(\frac{P_{\text{DC,available}}}{P_{\text{AC,PS}} \cdot R_{\text{DC/AC, desired}} + P_{\text{DC,embedded}}}\right) \tag{A.4}$$

$$N_{\text{defPS,upper}} = \mathit{Ceil}\left(\frac{33156.375\,kWdc}{5000\,kWac \cdot 1.2\dfrac{kWdc}{kWac} + 0}\right) = 6 \tag{A.5}$$

The updated DC power remaining for non-default power stations is calculated as:

$$P_{\text{DC,available}} = 33156.375\,kWdc - 5 \cdot 5000\,kWac \cdot 1.2\frac{kWdc}{kWac} = 3156.375\,kWdc \tag{A.6}$$

The lower and upper number of non-default power stations that can be installed is calculated as:

$$N_{\text{defPS,lower}} = \mathit{Floor}\left(\frac{P_{\text{DC,available}}}{P_{\text{AC,PS}} \cdot R_{\text{DC/AC, desired}} + P_{\text{DC,embedded}}}\right) \tag{A.7}$$

$$N_{\text{defPS,lower}} = \mathit{Floor}\left(\frac{3156.375\,kWdc}{2500\,kWac \cdot 1.2\dfrac{kWdc}{kWac} + 0}\right) = 1 \tag{A.8}$$

$$N_{\text{defPS,upper}} = \mathit{Ceil}\left(\frac{P_{\text{DC,available}}}{P_{\text{AC,PS}} \cdot R_{\text{DC/AC, desired}} + P_{\text{DC,embedded}}}\right) \tag{A.9}$$

$$N_{\text{defPS,upper}} = \mathit{Ceil}\left(\frac{3156.375\,kWdc}{2500\,kWac \cdot 1.2\dfrac{kWdc}{kWac} + 0}\right) = 2 \tag{A.10}$$

The possible combinations of power stations to evaluate are:

- 5 default power stations: 2229 strings can be installed and the resulting ratio would be 1.326.
- 6 default power stations: 2229 strings can be installed and the resulting ratio would be 1.105
- 5 default power stations and 1 non-default power station: 2229 strings can be installed and the resulting ratio would be 1.205
- 5 default power stations and 2 non-default power stations: 2229 strings can be installed and the resulting ratio would be 1.105

From the possible combinations, installing 5 default power stations and 1 non-default power station is selected as the optimal one, as all the strings available would be installed and the ratio is the one closest to the desired.

The optimal number of strings to install in one inverter is calculated as:

$$N_{\text{strings,inverter}} = Round\left(\frac{P_{\text{AC,inverter}} \cdot R_{\text{DC/AC, resulting}}}{P_{\text{DC,string}}} \cdot \frac{1}{N_{\text{string,structure}}}\right) \cdot N_{\text{strings,structure}} \tag{A.11}$$

$$N_{\text{strings,inverter}} = Round\left(\frac{2500\, kWac \cdot 1.2056 \frac{kWdc}{kWac}}{0.595\, kWdc/mod \cdot 25\, mods/string} \cdot \frac{1}{3}\right) \cdot 3 = 204 \tag{A.12}$$

The number of strings that have to be redistributed is calculated as:

$$N_{\text{strings, redistribution}} = N_{\text{strings, area}} - \sum_{i=1}^{N_{\text{inv, area}}} N_{\text{strings, i}} \tag{A.13}$$

$$N_{\text{strings, redistribution}} = 2229 - \sum_{i=1}^{N_{\text{inv, area}}} N_{\text{strings, i}} = 2229 - 11 \cdot 204 = -15\, strings \tag{A.14}$$

So, the number of inverters to adapt the optimal strings defined is:

$$N_{\text{inverters, adapt}} = \frac{Abs(N_{\text{strings, redistribution}})}{N_{\text{strings, structure}}} = \frac{Abs(-15)}{3} = 5\, inverters \tag{A.15}$$

15 strings need to be removed from 5 inverters, or 3 strings per inverter. As 5 default power stations were defined, 3 strings will be removed from one inverter in each of them.

After this calculation, the resulting combination of power stations that will give a DC/AC ratio of 1.2056 and will be composed by:

- 5 default power stations with 2 inverters, one with 201 strings and another with 204 strings.
- 1 non-default power station with 1 inverter with 204 strings.

Appendix B

Determining cable cross-sections

The assumptions made for the following examples are the following ones:

- The soil temperature equals 25°C.
- The ambient temperature equals 40°C.
- The soil resistivity equals 1 Km/W.
- The depth of cables are 700 mm for buried LV cables and 900 mm for MV cables.
- The MV cables are spaced 0.2 m between group centres and there is no space between LV cables.
- String cables are single core Cu cables fastened to the structures. XLPE is chosen for IEC and XHHN for NEC.
- Medium voltage cables are single core Al cables directly buried in trenches. XLPE is chosen for IEC and XHHN for NEC.
- The voltage drop is considered as 0.5 % for LV and MV cables.

B.1 Medium voltage cables

The power of the cable is 12 MVA. The voltage level is 30 kV and the length is 500 m. In addition, there are 10 lines that are group together to connect the plant with the substation. The short-circuit current equals 25 kA and the short-circuit time equals 1 s.

B.1.1 IEC standard

The operating current is calculated as:

$$I_{\text{load}} = \frac{S_{\text{VA}}}{V \cdot \sqrt{3}} = \frac{12 \cdot 10^6}{30 \cdot 10^3 \cdot \sqrt{3}} = 230\,A \tag{B.1}$$

The IEC standard followed to size a medium voltage cable is the IEC 60502-2. The reference conditions that the IEC standard takes as basis for its tables are the following ones:

- A maximum conductor temperature of 90 °C

- An ambient air temperature of 30 °C
- A ground temperature of 20 °C
- A depth of laying of 0.8 m
- A thermal resistivity of soil of 1.5 Km/W

As the medium voltage cable is directly buried, the ground temperature correction factor is given by Equation 3.3. The conductor is aluminium whose β equals 228 °C. The insulator material is XLPE whose operational temperature in normal conditions is $\theta_\mathrm{i} = 90$ °C.

$$CF_\mathrm{temp} = \left[\frac{\theta_\mathrm{i} - \theta_\mathrm{a}}{\theta'_\mathrm{i} - \theta'_\mathrm{a}} \cdot \frac{\beta + \theta'_\mathrm{i}}{\beta + \theta_\mathrm{i}}\right]^{\frac{1}{2}} = \left[\frac{90 - 25}{90 - 20} \cdot \frac{228 + 90}{228 + 90}\right]^{\frac{1}{2}} = 0.928 \tag{B.2}$$

The others corrections factors are given in the following table. In order to find them in the tables, there are few parameters that need to be taken into account.

First of all, this medium voltage cable is a single core cable. There are 10 circuits that are grouped together to link the power stations to the substations. In this case, according to IEC, a value of 10 current-carrying conductors should be considered to obtain the correction factor for a group of cables. Second, the cable is installed at a depth of 0.9 m and they are spaced 0.2 m between group centres. Last, the soil resistivity that is considered equals 1 Km/W.

Table B.1: Correction factors according to IEC standard for MV cables.

Correction Factors	For MV cables: IEC 60502-2	Correction factors
For soil thermal resistivities	Table B.14	≈ 1.19
For depths of laying	Table B.12	≈ 0.975
For groups of cables	Table B.19	0.54

Then, the sizing current is given by Equation 3.2.

$$I_\mathrm{sizing} = \frac{I_\mathrm{operating}}{CF} = \frac{230}{0.928 \cdot 1.19 \cdot 0.975 \cdot 0.54} = \frac{230}{0.58} = 395\,A \tag{B.3}$$

According to table B.3 of the IEC standard, the section chosen is 300 mm^2.

$$S = 300\,mm^2 \Rightarrow I_\mathrm{ccc} = 414\,A > I_\mathrm{sizing} = 395\,A \tag{B.4}$$

According to the short-circuit current criterion, the section is obtained using Equation 3.11. The short-circuit temperature of the XLPE is 250 °C.

$$S = \frac{I_\mathrm{sc} \cdot \sqrt{t}}{K \cdot \sqrt{ln\left(\frac{\theta_\mathrm{f} + \beta}{\theta_\mathrm{i} + \beta}\right)}} = \frac{25000 \cdot \sqrt{1}}{148 \cdot \sqrt{ln\left(\frac{250 + 228}{90 + 228}\right)}} = 266\,mm^2 \tag{B.5}$$

According to the voltage drop criterion, the section is obtained using Equation 3.19.

$$S = \frac{\sqrt{3} \cdot \rho(20°C) \cdot (1 + \alpha(\theta_i - 20)) \cdot L \cdot I}{\Delta V \cdot V} = \frac{\sqrt{3} \cdot 1/35 \cdot (1 + 0.00403(90 - 20)) \cdot 500 \cdot 230}{0.005 \cdot 30000} = 48\, mm^2 \tag{B.6}$$

Finally, the section of the cable is given by the following expression:

$$S = max\left(300\, mm^2, 266\, mm^2, 48\, mm^2\right) = 300\, mm^2 \tag{B.7}$$

B.1.2 NEC standard

The operating current is calculated as:

$$I_{\text{load}} = \frac{S_{\text{VA}}}{V \cdot \sqrt{3}} = \frac{12 \cdot 10^6}{30 \cdot 10^3 \cdot \sqrt{3}} = 230\, A \tag{B.8}$$

The reference conditions that the NEC standard takes as basis for its tables of MV cables are the following ones:

- A maximum conductor temperature of 90 °C
- An ambient air temperature of 40 °C
- A ground temperature of 20 °C
- A depth of laying of 0.9 m
- A thermal resistivity of soil of 0.9 Km/W

As the medium voltage cable is directly buried, the ground temperature correction factor is given by Equation 3.3. The conductor is aluminium whose β equals 228 °C. The insulator material is XHHN whose operational temperature in normal conditions is $\theta_i = 90$ °C.

$$CF_{\text{temp}} = \left[\frac{\theta_i - \theta_a}{\theta_i' - \theta_a'} \cdot \frac{\beta + \theta_i'}{\beta + \theta_i}\right]^{\frac{1}{2}} = \left[\frac{90 - 25}{90 - 20} \cdot \frac{228 + 90}{228 + 90}\right]^{\frac{1}{2}} = 0.928 \tag{B.9}$$

The others corrections factors are given in the following table. In order to find them in the tables, there are few parameters that need to be taken into account.

First of all, this medium voltage cable is a single core cable. There are 10 circuits that are grouped together to link the power stations to the substations. In this case, according to NEC, a value of 30 current-carrying conductors should be considered to obtain the correction factor for a group of cables. Second, the cable is installed at a depth of 0.9 m and they are spaced 0.2 m between group centres. Last, the soil resistivity that is considered equals 1 Km/W.

Table B.2: Correction factors according to NEC standard for MV cables.

Correction Factors	For MV cables: NEC	Correction factors
For soil thermal resistivities	IEEE Std 399-1997 - Table 13-7	≈ 0.91
For depths of laying	NEC Annex B, Section B.3(b)	1
For groups of cables	NEC Table B.310.15(B)(2)(11)	0.6

Then, the sizing current is given by Equation 3.6.

$$I_{\text{sizing}} = \frac{I_{\text{operating}}}{CF} = \frac{230}{0.928 \cdot 0.91 \cdot 1 \cdot 0.6} = 453\,A \tag{B.10}$$

According to table 310.60(C)(86) of the NEC standard, the section chosen is 750 kcmil.

$$S = 750\,kcmil \Rightarrow I_{\text{ccc}} = 550\,A > I_{\text{sizing}} = 453\,A \tag{B.11}$$

According to the short-circuit current criterion, the section is obtained using Equation 3.11. The short-circuit temperature of the XHHN is 250 °C.

$$S = \frac{I_{\text{sc}} \cdot \sqrt{t}}{K \cdot \sqrt{ln\left(\frac{\theta_{\text{f}}+\beta}{\theta_{\text{i}}+\beta}\right)}} = \frac{25000 \cdot \sqrt{1}}{148 \cdot \sqrt{ln\left(\frac{250+228}{90+228}\right)}} = 266\,mm^2 \tag{B.12}$$

According to the voltage drop criterion, the section is obtained using Equation 3.19.

$$S = \frac{\sqrt{3} \cdot \rho(20°C) \cdot (1+\alpha(\theta_{\text{i}}-20)) \cdot L \cdot I}{\Delta V \cdot V} = \frac{\sqrt{3} \cdot 1/35 \cdot (1+0.00403(90-20)) \cdot 500 \cdot 230}{0.005 \cdot 30000} = 48\,mm^2 \tag{B.13}$$

Finally, the section of the cable is given by the following expression:

$$S = max\left(750\,kcmil, 266\,mm^2, 48\,mm^2\right) = 750\,kcmil \approx 380\,mm^2 \tag{B.14}$$

B.2 Low voltage cables. String level

The power of the string is 10.585 kW. The MPP voltage is 1145 V and the length is 30 m. In addition, there are 24 strings that are group together to connect the structures to a string box. The short-circuit current of the modules equals 9.75 A.

B.2.1 IEC standard

The operating current is calculated as:

$$I_{\text{load}} = \frac{S_{\text{VA}}}{V \cdot \sqrt{3}} = \frac{10.585 \cdot 10^3}{1145 \cdot} = 9.24\,A \tag{B.15}$$

The IEC standard followed to size a low voltage cable is the IEC 60364-5-52. The reference conditions that the IEC standard takes as basis for its tables are the following ones:

- A maximum conductor temperature of 90 °C for XLPE and 70 °C for PVC.
- An ambient air temperature of 30 °C
- A ground temperature of 20 °C
- The depth of laying is not considered.
- A thermal resistivity of soil of 2.5 Km/W

As the low voltage cable is fastened to a structure, the ambient temperature correction factor is given by Equation 3.3. The conductor is copper whose β equals 234.5 °C. The insulator material is XLPE whose operational temperature in normal conditions is $\theta_{\text{i}} = 90$ °C.

$$CF_{\text{temp}} = \left[\frac{\theta_{\text{i}} - \theta_{\text{a}}}{\theta'_{\text{i}} - \theta'_{\text{a}}} \cdot \frac{\beta + \theta'_{\text{i}}}{\beta + \theta_{\text{i}}}\right]^{\frac{1}{2}} = \left[\frac{90 - 40}{90 - 30} \cdot \frac{234.5 + 90}{234.5 + 90}\right]^{\frac{1}{2}} = 0.83 \tag{B.16}$$

The others corrections factors are given in the following table. In order to find them in the tables, there are few parameters that need to be taken into account.

First of all, this low voltage cable is a single core cable. There are 24 circuits that are grouped together to link the structures to a string box. In this case, according to IEC, a value of 24 current-carrying conductors should be considered to obtain the correction factor for a group of cables. Second, the cable is fastened to a structure and they are touching among each other.

Table B.3: Correction factors according to IEC standard for LV cables.

Correction Factors	For MV cables: IEC 60502-2	Correction factors
For groups of cables	Table B.52.17	0.72

Then, the sizing current is given by Equation 3.2.

$$I_{\text{sizing}} = \frac{I_{\text{operating}}}{CF} = \frac{9.24}{0.833 \cdot 0.72} = 15.4\,A \tag{B.17}$$

According to table B.52.12 of the IEC standard, the section chosen is 1.5 mm^2.

$$S = 1.5\,mm^2 \Rightarrow I_{\text{ccc}} = 29\,A > I_{\text{sizing}} = 15.4\,A \tag{B.18}$$

According to the voltage drop criterion, the section is obtained using Equation 3.20.

$$S = \frac{2 \cdot \rho(20°C) \cdot (1 + \alpha(\theta_{\mathrm{i}} - 20)) \cdot L \cdot I}{\Delta V \cdot V} = \frac{2 \cdot 1/56 \cdot (1 + 0.00392(90 - 20)) \cdot 30 \cdot 15.4}{0.005 \cdot 1145} = 3.7\, mm^2 \tag{B.19}$$

Finally, the section of the cable is given by the following expression:

$$S = max\left(1.5\, mm^2\,,\ 3.7\, mm^2\right) = 3.7\, mm^2 \Rightarrow 4\, mm^2\ (commercial\, section) \tag{B.20}$$

B.2.2 NEC standard

The sizing current is calculated by Equation 3.5.

$$I_{\mathrm{sizing}} = max\left(I_{\mathrm{corrected}}\,,\ I_{\mathrm{OCPD}}\right) \tag{B.21}$$

The reference conditions that the NEC standard takes as basis for its tables of LV cables are the following ones:

- A maximum conductor temperature of 90 °C for XHHN insulation and 75 °C for THHN insulation.
- An ambient air temperature of 30 °C
- A ground temperature of 20 °C
- A thermal resistivity of soil of 0.9 Km/W

As the low voltage cable is fastened to a structure, the ambient temperature correction factor is given by Equation 3.3. The conductor is copper whose β equals 234.5 °C. The insulator material is XHHN whose operational temperature in normal conditions is $theta_{\mathrm{i}} = 90$ °C.

$$CF_{\mathrm{temp}} = \left[\frac{\theta_{\mathrm{i}} - \theta_{\mathrm{a}}}{\theta'_{\mathrm{i}} - \theta'_{\mathrm{a}}} \cdot \frac{\beta + \theta'_{\mathrm{i}}}{\beta + \theta_{\mathrm{i}}}\right]^{\frac{1}{2}} = \left[\frac{90 - 40}{90 - 30} \cdot \frac{234.5 + 90}{234.5 + 90}\right]^{\frac{1}{2}} = 0.83 \tag{B.22}$$

The others corrections factors are given in the following table. In order to find them in the tables, there are few parameters that need to be taken into account.

First of all, this low voltage cable is a single core cable. There are 24 circuits that are grouped together to link the structures to a string box. In this case, according to NEC, a value of 48 current-carrying conductors should be considered to obtain the correction factor for a group of cables. Second, the cable is fastened to a structure and they are touching among each other.

Table B.4: Correction factors according to NEC standard for LV cables.

Correction Factors	For MV cables: NEC	Correction factors
For groups of cables	NEC Table B.310.15(B)(2)(11)	0.5

Then, the corrected current is given by Equation 3.6.

$$I_{\text{corrected}} = \frac{1.25 \cdot I_{\text{sc}}}{CF} = \frac{1.25 \cdot 9.75}{0.83 \cdot 0.5} = 29\,A \tag{B.23}$$

On the other hand, the I_{OCPD} is calculated based on Equation 3.7.

$$1.25 \cdot (1.25 \cdot I_{\text{sc}}) = 1.56 \cdot 9.75 = 15.21\,A \Rightarrow I_{\text{OCPD}} = 20\,A \tag{B.24}$$

Then, the sizing current is calculated as:

$$I_{\text{sizing}} = max\,(29\,A,\ 20\,A) = 29\,A \tag{B.25}$$

According to table 310.15(B)(17) of the NEC standard, the section chosen is 14 AWG.

$$S = 14\,AWG \Rightarrow I_{\text{ccc}} = 35\,A > I_{\text{sizing}} = 29\,A \tag{B.26}$$

According to the voltage drop criterion, the section is obtained using Equation 3.20.

$$S = \frac{2 \cdot \rho(20°C) \cdot (1 + \alpha(\theta_{\text{i}} - 20)) \cdot L \cdot I}{\Delta V \cdot V} = \frac{2 \cdot 1/56 \cdot (1 + 0.00392(90 - 20)) \cdot 30 \cdot 15.4}{0.005 \cdot 1145} = 3.7\,mm^2 \tag{B.27}$$

Finally, the section of the cable is given by the following expression:

$$S = max\,\left(14\,AWG,\ 3.7\,mm^2\right) = 3.7\,mm^2 \Rightarrow 10\,AWG\,(commercial\,section) \tag{B.28}$$

Appendix C

Determining electrical characteristics of the cable

After selecting the cross-section based on the three criteria that have been presented in this methodology, the electrical characteristics of the cable are computed. These are the voltage drop, the temperature and the short-circuit current that the cables can withstand.

C.1 Determining the electrical characteristics of a medium voltage cable

The following example is based on the cable that was calculated in Subsection B.1.1. At the end, the cable cross-section was 300 mm^2.

C.1.1 Temperature of the cable

The temperature of the cable is calculated using Equation 3.8.

$$\theta = \theta_{\text{amb}} + (\theta_{\text{i}} - \theta_{\text{amb}}) \cdot \left(\frac{I}{I_{\text{a}}}\right)^2 \tag{C.1}$$

$$\theta = 25 + (90 - 25) \cdot \left(\frac{230}{414 \cdot 0.58}\right)^2 = 84\,^{\circ}C < \theta_{\text{i}} = 90\,^{\circ}C \Rightarrow OK \tag{C.2}$$

C.1.2 Voltage drop

The voltage drop is calculated using the following formula:

$$\Delta V = \frac{\sqrt{3} \cdot \rho(20^{\circ}C) \cdot (1 + \alpha(84^{\circ}C - 20)) \cdot L \cdot I}{S \cdot V} \tag{C.3}$$

$$\Delta V = \frac{\sqrt{3} \cdot 0.0359 \cdot 500 \cdot 230}{300 \cdot 30000} = 0.08\% < \Delta V_{\text{input}} = 0.5\% \Rightarrow OK \tag{C.4}$$

C.1.3 Withstand short-circuit current

The withstand short-circuit current that the cable can withstand is calculated as follows:

$$I_{\text{sc}} = \frac{S \cdot K \cdot \sqrt{ln\left(\frac{\theta_{\text{f}} + \beta}{\theta_{\text{i}} + \beta}\right)}}{\sqrt{t}} \tag{C.5}$$

$$I_{\text{sc}} = \frac{300 \cdot 148 \cdot \sqrt{ln\left(\frac{250 + 228}{90 + 228}\right)}}{\sqrt{1}} = 28.2\,kA > I_{\text{sc grid}} = 25\,kA \Longrightarrow OK \tag{C.6}$$