Interconnection Facility Methodology

A methodology to design an air-insulated substation

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[3]Provided essential software knowledge

Abstract

This methodology describes the basic design process to design a step-up substation which is connected to a solar PV plant. The objective of this document is to present the main steps that are necessary to determine the electrical characteristics of a substation.

There are many different ways in which a substation can be designed. Each way would have some advantages and disadvantages. The author of this methodology has decided on a structure which follows the work of the substation's experts during many decades:

- The circuit arrangement of the substation is selected and the number of transformer and line bays are established.
- The insulation coordination is computed to operate the substation satisfactorily not only under normal operating conditions but also in the presence of transient and temporary overvoltages.
- The safety distances that will be maintained within the substation's field are specified.
- The main components of the substation are determined according to their standards. Power transformers, surge arresters, instrument transformers, circuit breakers, disconnectors and grounding devices, among others are studied in the methodology.
- For the double busbar substations, the following aspects are considered to size the busbars: current-carrying requirements (continuous and short circuit), environmental considerations (ice, wind, weight, etc.), physical constraints, future requirements of the substation and corona interference.

Note: All the calculations that are presented in this methodology are carried out in accordance with the latest IEC and IEEE standards.

Contents

List of Figures

List of Tables

Chapter 1

Selecting Circuit Arrangements

This chapter summarizes the possible electrical substations that the user will be able to obtain as well as the conditions that every solution will satisfy.

1.1 Type of electrical arrangement

The software automatically generates a solution for an electrical substation. The possible layouts that can be obtained are the following ones:

1. A switching and breaking station is the solution that operates at a single voltage level, meaning there is no power transformer. A switching station can be defined as a group of cubicles that are protected by a switchgear, whose objective is to break or split a distribution power line into one or several output lines. An illustration of this type of substations is represented in Figure 1.1

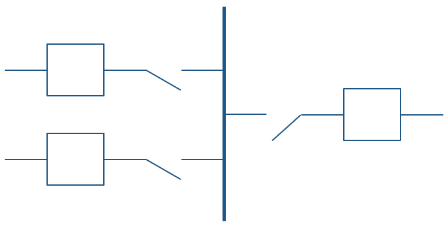

Figure 1.1: Switching and breaking station configuration. Source: Own elaboration

2. A line to transformer substation is the type that consists of one transformer bay. In addition, a medium voltage cubicle will connect the photovoltaic plant with the power transformer. Figure 1.2 illustrates the line to transformer substation.

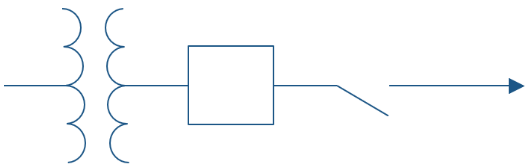

Figure 1.2: Line to transformer substation configuration. Source: Own elaboration

3. A single busbar substation is the substation that consists of one or more transformer bays and one or more outgoing circuits which are connected to each other by a rigid bus. The connection between the photovoltaic plant and the power transformers is made through one or more medium voltage cubicles. This type of substation is represented in Figure 1.3.

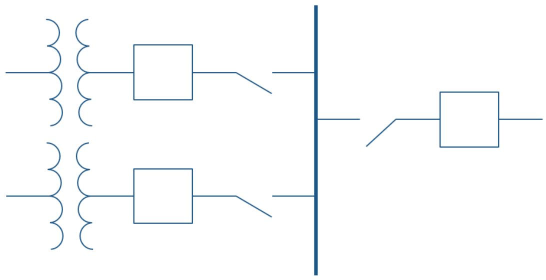

Figure 1.3: Simple busbar substation configuration. Source: Own elaboration

4. A double busbar substation is the option that consists of one or more transformer bays and one or more outgoing circuits which are connected to each other by two rigid buses. The connection between the photovoltaic plant and the power transformers is made through one or more medium voltage cubicles. An illustration of such a substation can be seen in Figure 1.4.

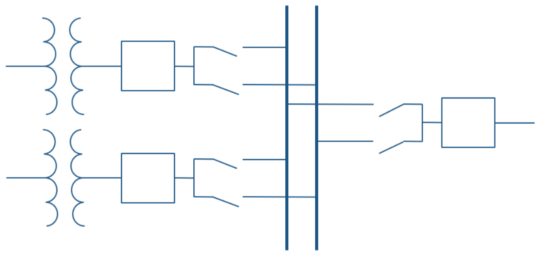

Figure 1.4: Double busbar substation configuration. Source: Own elaboration

The generated solution will depend on the plant's installed capacity, the medium voltage system, and the number of power transformers.

1.2 Switching and breaking station

The switching and breaking station consists of a number of cubicles that allow modularity. In addition, a modular design provides the capacity to extend and adapt the station to the development of the network and to replace the modules without interrupting the supply. Each cubicle will include different protection or measurement devices depending on the type of the cubicle.

In general, a switching and breaking station has some cubicles that are designed for a feeder function and others that are designed for either measuring the voltage and the current (metering function) or for protecting the station against over voltages or faults (circuit breaker or fuse protection function).

The cubicles that are incorporated in the station are the following:

Feeder function

A feeder cubicle enables the communication with the main busbar. In addition to the feeder cubicle that connects the station to the grid, there will be as many feeder cubicles as medium voltage power lines leaving the photovoltaic plant. A feeder cubicle is equipped with:

- A switch-disconnector. Its main parameters that are given are the rated current and the short-circuit current.
- The cables coming from the photovoltaic plant or those that feed the station. Up to six repetitions per cable can be connected to the feeder cubicles.

Metering function

A metering cubicle provides information about the operating voltage and the current that flows through the cubicle. It is equipped with:

- A current transformer.
- A voltage transformer.

Circuit breaker protection function

It provides general protection for feeders or instrument transformers as well as providing connection and disconnection operations. A protection cubicle is equipped with:

- A switch-disconnector.
- A vacuum circuit breaker.

Fuse protection function

It provides general protection for feeders or instrument transformers as well as providing connection and disconnection operations. Furthermore, an auxiliary service line with a step down transformer is connected to the fuse protection cubicle. The 100 kVA auxiliary transformer will step down the voltage from the medium voltage level to a low voltage level that equals to 400 V. A fuse protection cubicle is equipped with:

- A switch-disconnector.
- A fuse.

Note that, for switching and breaking stations with a Battery Energy Storage System (BESS) connected, the fuse will be replaced by a circuit breaker.

1.3 Line to transformer substation

The line to transformer substation connects the PV plant to the grid without having a busbar. It stands out for being the simplest substation layout. The main devices that will be part of a line to transformer substation are:

- A power transformer.
- A surge arrester that protects the secondary winding of the power transformer.
- A surge arrester that protects the primary winding of the power transformer.
- A grounding device for the secondary winding of the power transformer.

- A circuit breaker.
- An earthing disconnector.
- A current transformer.
- A voltage transformer.
- A surge arrester that protects the end of the overhead line.

1.4 Single busbar substation

The single busbar substation can be split into three levels: the transformer bay, the output circuit level, and the buses level. The principal elements that must be included in every level are presented below.

Transformer bay

- A power transformer.
- A surge arrester that protects the secondary winding of the power transformer.
- A surge arrester that protects the primary winding of the power transformer.
- A grounding device for the secondary winding of the power transformer.
- A circuit breaker.
- A disconnector.
- A current transformer.

Output circuit level

- A surge arrester that protects the end of the overhead line.
- A circuit breaker.
- A disconnector.
- A current transformer.
- A voltage transformer.
- An earthing disconnector.

Buses level

The buses are used to connect bays into an existing substation. The software will give all the information about the dimensions of the buses such as material, external diameter, internal diameter, and section while taking into account external conditions, loads, post insulators, etc... In addition, a voltage transformer has been considered.

1.5 Double busbar substation

The double busbar substation can be split into three levels: the transformer bay, the output circuit level and the buses level. The principal elements that should be included in every level are presented below.

Transformer bay

- A power transformer.
- A surge arrester that protects the secondary winding of the power transformer.
- A surge arrester that protects the primary winding of the power transformer.
- A grounding device for the secondary winding of the power transformer.
- A circuit breaker.
- Two disconnectors.
- A current transformer.

Output circuit level

- A surge arrester that protects the end of the overhead line.
- A circuit breaker.
- Two disconnectors.
- A current transformer.
- A voltage transformer.
- An earthing disconnector.

Buses level

The buses are used to connect bays into an existing substation. The software will give all the information about the dimensions of the buses such as material, external diameter, internal diameter, and section,while taking into account external conditions, loads, post insulators, etc...

In the bus level, a bus coupler has been included. The bus coupler allows the two busbars to either run separately or to run with the bus coupler's breaker closed or open. In addition, two voltage transformers (one per each bus) have been considered.

1.6 Selection of the type of arrangement

The criteria which have been set to choose between the possible types of substations are presented below.

The switching and breaking station must always fulfil that the total current is lower than 2500 A.

$$\boxed{I_t \leq 2500\,A} \tag{1.1}$$

$$\boxed{S_{pv} \leq 100\,MVA} \tag{1.2}$$

Where:

- I_t is the total current of the PV plant. [A]
- S_{pv} is the installed capacity of the PV plant. [MVA]

The line to transformer substation fulfills that the number of transformer bays is equal to one.

$$\boxed{N_{bays} = 1} \tag{1.3}$$

Where:

- N_{bays} is the total of substation bays.

The single busbar substation fulfils that the number of transformer bays is greater than one. It also meets that the total operating current of the PV plant is lower than three times the maximum admissible current per bay.

$$\boxed{I_t \leq 3 \cdot I_{\text{op-mv}}} \tag{1.4}$$

$$\boxed{N_{\text{t/out-bays}} > 1} \tag{1.5}$$

Where:

- I_t is the total current of the PV plant. [A]
- $I_{\text{op-mv}}$ is the current that flows through the medium voltage level, calculated by Equation 2.3. [A]
- $N_{\text{t/out-bays}}$ is the number of transformer/output bays.

The double busbar substation fulfils that the number of transformer bays is greater than one. Moreover, it meets the criteria that the total operating current of the PV plant is greater than three times the maximum admissible current per bay.

$$\boxed{I_t > 3 \cdot I_{\text{op-mv}}} \tag{1.6}$$

$$\boxed{N_{\text{t/out-bays}} > 1} \tag{1.7}$$

Where:

- I_t is the total current of the PV plant. [A]
- $I_{\text{op-mv}}$ is the current that flows through the medium voltage level, calculated by Equation 2.3. [A]
- $N_{\text{t/out-bays}}$ is the number of transformer/output bays.

Chapter 2

Determination of the number of substation bays

In this chapter, the main criteria to split the substation in different bays will be presented. The number of transformer bays will be determined automatically based on four criteria. The number of output bays will also be established automatically and this decision will be calculated in accordance to one criterion.

2.1 Determination of the number of transformer bays

The number of transformer bays will be determined automatically based on four criteria, which are presented in this section.

As mentioned in Chapter 3, the operating short-circuit current that could affect the medium voltage system shall be lower than the design short-circuit current that has been selected to size the substation components.

So, the first criterion that a transformer bay must fulfill is given in Equation 2.1.

$$\boxed{I_{\text{op-sc}} \leq I_{\text{sc}}} \tag{2.1}$$

Where:

- $I_{\text{op-sc}}$ is the operating short-circuit current per bay at medium voltage level. [A]
- I_{sc} is the design short-circuit current at the substation input. [A]

In order to establish the number of transformer bays, one of the key parameters is the design current that can flow per bay in the medium voltage system. The design short-circuit current limits this admissible current, which is calculated using Equation 2.2.

$$I_{\text{des}} = I_{\text{sc}} \cdot z_{\text{sc}} \tag{2.2}$$

Where:

- I_{des} is the maximum design current that can flow through a transformer bay at medium voltage level. [A]
- I_{sc} is the design short-circuit current at the substation input. [A]
- z_{sc} is short-circuit impedance of the power transformer in parts per one.

The operating current that actually flows per transformer bay is calculated using Equation 2.3.

$$I_{\text{op-mv}} = \frac{P_t}{U\sqrt{3}} \tag{2.3}$$

Where:

- $I_{\text{op-mv}}$ is the current that flows through the medium voltage level. [A]
- P_t is the capacity of the power transformer. [VA]
- U is the medium voltage level. [V]

So, the second criterion that a transformer bay may fulfil is given in Equation 2.4.

$$\boxed{I_{\text{op-mv}} \leq I_{des}} \tag{2.4}$$

Where:

- I_{des} is the maximum design current that can flow through a transformer bay at medium voltage level. [A]
- $I_{\text{op-mv}}$ is the current that flows through the medium voltage level. [A]

According to [1], to obtain a total load that is equal to the total installed power of the PV plant, the power transformers must have the same short-circuit impedance. For that reason, the short-circuit impedances of the power transformers per bay may be equal. The third criterion that a transformer bay may fulfil is given in Equation 2.5.

$$\boxed{z_{\text{sc-i}} = z_{\text{sc-j}}} \tag{2.5}$$

Where:

- $z_{\text{sc-i}}$ is short-circuit impedance of the power transformer for the bay i.
- $z_{\text{sc-j}}$ is short-circuit impedance of the power transformer for the bay j.

The cables that connect the primary medium voltages with a power transformer should withstand the total current that they are carrying. These cables are calculated based on Section 6.8. The last criterion that a transformer bay may fulfil is given in Equation 2.6.

$$\boxed{I_{\text{op-mv}} \leq I_{ccc}} \tag{2.6}$$

Where:

- I_{ccc} is the current-carrying capacity of the selected cable after applying the standard correction factors. [A]
- $I_{\text{op-mv}}$ is the current that flows through the medium voltage level. [A]

2.2 Determination of the type of power transformer

The type of the power transformer depends on the size of the plant, in other words, on the total secondary current calculated following Equation 2.3.

If the total current is strictly higher than 10000 A, a three-winding transformer will be designed to step-up the voltage.

2.3 Determination of the number of output bays

The number of output bays will be determined automatically based on only one criterion. This criterion is based on the rated characteristics of the switchgear. That is, a rated current of 4000 A has been taken as the maximum rated current for the switchgear that is located in the output bays.

So, the criterion that an output bay may fulfil is given in Equation 2.7.

$$\boxed{I_{\text{op-hv}} \leq \frac{4000}{f_{\text{s}}} A} \tag{2.7}$$

Where:

- $I_{\text{op-hv}}$ is the current that flows through the HV output bay. [A]
- f_{s} is a safety factor that equals 1.25.

Chapter 3

Calculation of the short-circuit currents

The calculation of the short-circuit currents is key to correctly size the number of substation bays and the electrical characteristics of the devices. In this section, four short-circuit currents will be presented.

- The design short-circuit current for both high and medium voltage systems. Design short-circuit currents are considered to size the substation switchgear.
- The operating short-circuit currents according to [2] and [3] following both the IEC and the IEEE standards respectively.
- The peak short-circuit current for both the high and medium voltage systems, according to [2].
- The thermal short-circuit current for both the high and medium voltage systems, according to [2].

The first criterion that has to be fulfilled is that the operating short-circuit current that could affect the the medium voltage system shall be lower than the design short-circuit current that has been selected to size the substation components.

$$I_{\text{op-sc}} \leq I_{\text{sc}} \tag{3.1}$$

Where:

- $I_{\text{op-sc}}$ is the operating short-circuit current at the substation input. [A]
- I_{sc} is the design short-circuit current at the substation input. [A]

3.1 Design short-circuit currents

The design-short circuit currents are obtained directly from the maximum voltage for the system and they are linked to a short-circuit power from the grid. They have been calculated based on both the IEC standard [4], [5], [6] and [7] and the IEEE standard [8].

Table 3.1: Short-circuit power and currents According to IEC. Source: Own elaboration

Highest voltage for equipment U_m [kV]	Design short-circuit current I_{sc} [kA]	Short-circuit power S_{sc} [MVA]
7.2	25	250
12	25	450
17.5	25	650
24	25	900
36	25	1350
52	31.5	2500
72.5	31.5	3500
100	31.5	4900
123	31.5	6000
145	40	9000
170	40	10000
245	50	19000
300	50	23000
362	50	28000
420	50	32000
550	63	50000
800	63	70000

Table 3.2: Short-circuit power and currents According to IEEE. Source: Own elaboration

Highest voltage for equipment U_m [kV]	Design short-circuit current I_{sc} [kA]	Short-circuit power S_{sc} [MVA]
48.3	31.5	2500
72.5	31.5	3500
121	31.5	6000
145	40	9000
169	40	10000
242	50	19000
362	50	28000
550	63	50000
765	63	70000
800	63	70000

3.2 Operating short-circuit currents

The operating short-circuit current at the substation input (medium voltage level) has been calculated based on the impedance method proposed in [2]. The step by step calculation of the impedance method is not introduced in this methodology because it is out of scope. However, some important impedance formulas are presented.

Due to the topology of the problem, that is, the photovoltaic plant is connected to the grid thanks to a substation that is made by one or several power transformers, it can be simplified if the effects of two main elements: an ideal external network and one/several two-winding power transformers are studied.

This calculation method consists of defining several nodes in which the short-circuit current will be studied. Between those nodes, the impedance of the different elements that belong to the grid will be obtained. The short-circuit current in a node is given by Equation 3.2.

$$I_{\text{op-sc}} = \frac{c \cdot U}{Z \cdot \sqrt{3}} \tag{3.2}$$

Where:

- $I_{\text{op-sc}}$ is the operating short-circuit current at the substation input. [A]
- c is a voltage factor that equals to 1.05 if $U_{\text{m}} < 1$ kV and equals to 1.1 if $U_{\text{m}} > 1$ kV. As for the IEEE standard, the voltage factor is not considered; hence, it equals to 1 in the equation.
- U is the voltage level. [V]
- Z is a impedance. [Ω]

The internal impedance of a high-voltage network or a medium-voltage network can then be determined according to Equation 3.3.

$$Z_{\text{network}} = \frac{U^2}{S_{\text{sc}}} \tag{3.3}$$

Where:

- Z_{network} is the internal impedance of a network. [Ω]
- U is the voltage level. [V]
- S_{sc} is the short-circuit power [VA] given by Table 3.1 for the IEC standard and by Table 3.2 for the IEEE standard.

The impedance of a two-windings transformer is calculated using Equation 3.4.

$$Z_{\text{t}} = \frac{U^2}{S_{\text{t}}} \cdot \frac{z_{\text{sc}}}{100} \tag{3.4}$$

Where:

- Z_{t} is the impedance of a two-windings transformer. [Ω]
- U is the voltage level. [V]
- S_{sc} is the transformer capacity. [VA]
- z_{sc} is the short-circuit impedance of the transformer given by Table 6.1 [%] according to the IEC standard and by Table 6.2 [%] following the IEEE standard.

3.3 Peak short-circuit currents

The peak short-circuit current can be calculated using Equation 3.5.

$$I_{\text{p}} = I_{\text{op-sc}} \cdot \kappa \sqrt{2} \tag{3.5}$$

Where:

- I_p is the peak short-circuit current. [A]
- $I_{op\text{-}sc}$ is the operating short-circuit current at the substation input. [A]
- κ is a network factor.

The factor κ shall be obtained from Equation 3.6.

$$\kappa = 1.02 + 0.98e^{(-3R/X)} \tag{3.6}$$

Where:

- κ is a network factor.
- $\frac{R}{X}$ is the resistance-reactance ratio of the network that equals 0.07.

3.4 Thermal short-circuit currents

The thermal equivalent short-circuit current can be calculated using Equation 3.7.

$$I_{th} = I_{op\text{-}sc}\sqrt{m+n} \tag{3.7}$$

Where:

- I_{th} is the thermal equivalent short-circuit current. [A]
- $I_{op\text{-}sc}$ is the operating short-circuit current at the substation input. [A]
- n is a factor for heat effect for AC components which equals 1.
- m is a factor for heat effect for DC components which is derived from Equation 3.8.

The factor m shall be obtained from Equation 3.8.

$$m = \frac{1}{2 \cdot f \cdot T_k \cdot ln(\kappa - 1)} \cdot \{e^{4 \cdot f \cdot T_k \cdot ln(\kappa-1)} - 1\} \tag{3.8}$$

Where:

- m is the factor for heat effect for DC components.
- κ is a network factor.
- f is the system frequency. [Hz]
- T_k is the duration of the short-circuit current that equals 1. [s]

Chapter 4

Insulation Coordination

In this chapter, the insulation levels and clearance distances for air insulated substations are calculated based on [9], [10] and [11] in obedience with the IEC standard and based on [12] and [13] in compliance with the IEEE standard . The objective is to specify the procedure for the selection of the rated withstand voltages for the substation equipment's insulation.

After selecting the rated withstand voltages, the associated clearance distances will be recommended.

4.1 Introduction

This chapter calculates the insulation levels according to [9] for both class I (1 - 245 kV) and class II (245 - 800 kV) substations following the international standard and to [12] for class I (15 - 242 kV) and class II (242 - 800 kV).

The process followed in accordance with the IEC standard is the following:

First, the representative values for the temporary, slow-front, and fast-front overvoltages are calculated. Because the grid characteristics are unknown, some estimation will be made in the study.

Afterwards, the coordination overvoltages are computed. In this case, a coordination factor will be applied. Later, two correction factors are applied to obtain the required overvoltages. These correction factors take into account the differences in the dielectric strength between service and test conditions.

Once the required overvoltages are calculated, the assigned standard overvoltages are obtained. These standard rated voltages are linked to the highest voltage for equipment.

On the other hand, the process followed to calculate the insulation coordination according to the IEEE standard is the following:

First, the system voltage stresses for the overvoltage's classes are determined: switching, lightening, and temporary and that is for the phase-to-phase and phase-to-ground configurations.

Finally, depending on the voltage, the assigned standard voltage stresses are obtained, which depend on the maximum voltage of the equipment.

4.2 General procedure for insulation coordination

The procedure for insulation coordination's calculation consists of selecting a number of standard rated withstand voltages based on the highest voltage for the equipment. In addition, depending on the class of the substation (class I or class II), the procedure varies. Hence, the objective is to establish the minimal phase-to-earth and phase-to-phase clearance distances corresponding to the standard voltages.

Following the IEC standard, the classes are as follow:

- Class I: From 1 kV to 245 kV (included). This range applies to both distribution and transmission lines.
- Class II: For main transmission substation with high voltages above 245 kV.

According to the IEEE standard, the classes are as follow:

- Class I: From 1 kV to 242 kV (included). This range applies to both distribution and transmission lines.
- Class II: For main transmission substation with high voltages above 242 kV.

For class I substations, temporary and fast-front overvoltages,which are the temporary and the basic lightening voltage or BIL in the IEEE standard, are calculated to obtain the standard rated withstand voltages. The slow-front overvoltages are also computed following the IEC; and later, converted to temporary and to fast-front overvoltages. In some cases, slow-front converted values are higher than temporary or fast-front voltages and for that reason, they have to be taken into account.

For class II substations, the withstand voltages will depend on the slow-front, named the basic switching voltage or BSL in the IEEE standard, and fast-front overvoltages or BIL. In addition, the temporary overvoltages are computed, however, they are converted to slow-front overvoltages when calculating in accordance to IEC. These overvoltages will have a significant role if they are greater than slow-front and fast-front overvoltages.

Moreover, the first step to obtain the standard rated withstand voltages is to select the highest voltage for the equipment, given in Table 4.1 for the IEC standard and in Table 4.2 for the IEEE. This value will be considered to choose the withstand voltages from the standard.

Finally, the results will be a set of withstand voltages for internal and external insulation and for both phase-to-phase and phase-to-earth configurations. Once these standard rated withstand voltages are defined, the clearance distances are directly obtained.

The lightning arresters that are installed in the substation are calculated to have a good estimation of the insulation coordination. These devices will protect the substation equipment from overvoltages; and the complete model to obtain their most important parameters is presented in Subsection 6.3.1. The lightning and switching impulse protective levels play an important role to determine the representative fast-front and slow-front overvoltages.

Table 4.1: Highest voltage for the equipment according to IEC [11]

Highest voltages for equipment U_m [kV]
3.6
7.2
12
17.5
24
36
52
72.5
100
123
145
170
245
300
362
420
550
800

Table 4.2: Highest voltage for the equipment according to IEEE [13]

Highest voltages for equipment U_m [kV]
15
26.2
36.2
48.3
72.5
121
145
169
242
362
420
550
800
1200

4.2.1 Class I insulation coordination procedure

To establish a minimum recommended phase-to-earth and phase-to-phase clearance distances following the international standard, the following steps are necessary:

1. Determination of the representative temporary, slow-front, and fast-front overvoltages.
2. Application of the coordination factor to set the coordination overvoltages.

3. Calculation of the required overvoltages by applying a security factor and the atmospheric correction factors.
4. Conversion of the slow-front overvoltages to temporary and fast-front overvoltages by applying conversion factors.
5. Identification and selection of the standard rated withstand voltages in regards to the required overvoltages by referring to the highest voltages for the equipment.
6. If some required voltages are higher than the maximum standard rated withstand voltage for a specific highest voltage for equipment, a greater value of the standard voltage is selected even though the highest voltage is superior.
7. Selection of the minimum rod-structure and conductor-structure clearance distances for the standard rated withstand voltages that have been selected.
8. Identification of the phase-to-earth and phase-to-phase distances.

As for the IEEE standard, to determine the minimum recommended phase-to-phase and phase-to-earth clearance distances, the following steps are required:

1. Determination of the Basic Lightening impulse level or lightning-impulse withstand voltage (BIL) as well as the temporary overvoltages (short-duration withstand voltage) by applying protective margin and atmospheric correction factors.
2. Identification and selection of the standard rated BIL and standard temporary voltages in regard to the calculated BIL and short-duration withstand voltage by referring to the highest voltages for the equipment.
3. If some required voltages are higher than the maximum standard rated withstand voltage for a specific highest voltage for equipment, a greater value of the standard voltage is selected even though the highest voltage is superior.
4. Selection of the minimum rod-structure and conductor-structure clearance distances for the standard rated withstand voltages that have been selected.
5. Identification of the phase-to-earth and phase-to-phase distances.

4.2.2 Class II insulation coordination procedure

To establish a minimum recommended phase-to-earth and phase-to-phase clearance distances in obedience with the IEC standard, the following steps has been followed:

1. Determination of the representative temporary, slow-front, and fast-front overvoltages.
2. Application of the coordination factor to set the coordination overvoltages.
3. Calculation of the required overvoltages by applying a security factor and the atmospheric correction factors.
4. Conversion of the temporary overvoltages to slow-front overvoltages by applying conversion factors.
5. Identification and selection of the standard rated withstand voltages in regards to the required overvoltages by referring to the highest voltages for the equipment.
6. If some required voltages are higher than the maximum standard rated withstand voltage for a specific highest voltage for equipment, a greater value of the standard voltage is selected even though the highest voltage is superior.

7. Selection of the minimum rod-structure and conductor-structure clearance distances for the standard rated withstand voltages considering phase-to-earth configurations, and selection of the minimum conductor-conductor and rod-conductor clearance distances for phase-to-phase configurations.
8. Identification of the phase-to-earth and phase-to-phase distances.

On the other hand, to establish a minimum recommended phase-to-earth and phase-to-phase clearance distances in obedience with the IEEE standard, the following steps has been followed:

1. Determination of the Basic Lightening impulse level (BIL) and the Basic Switching Impulse Insulation level (BSL) by applying protective margin and atmospheric correction factors.
2. Identification and selection of the standard rated withstand voltages in regards to the BIL and BSL by referring to the highest voltages for the equipment.
3. If some required voltages are higher than the maximum standard rated withstand voltage for a specific highest voltage for equipment, a greater value of the standard voltage is selected even though the highest voltage is superior.
4. Selection of the minimum rod-rod clearance distances for the standard rated withstand voltages considering phase-to-earth and phase-to-phase configurations.
5. Identification of the phase-to-earth and phase-to-phase distances.

4.3 Determination of the representative voltages and overvoltages

The overvoltages that affect the insulation of the equipment of the substation shall be calculated by means of a grid analysis. However, by following the IEC procedure, it is possible to estimate the representative overvoltages. In subsections Subsection 4.3.1, Subsection 4.3.2 and Subsection 4.3.3, a simplified method is presented in order to define the representative overvoltages for temporary, slow-front, and fast-front overvoltages.

4.3.1 Temporary overvoltages

The representative temporary overvoltages can occur due to:

- Earth faults.
- Load rejections.
- Resonance.
- Synchronization.
- A combination of the previous effects.

For voltage systems higher than 36 kV, earth faults and load rejections are the two main sources that cause temporary overvoltages. The earth fault and the load rejection factors can be determined by grid studies. As the grid characteristics are unknown, these factors are estimated.

The maximum representative phase-to-earth and phase-to-phase overvoltages are calculated using Equation 4.1 and Equation 4.2

$$U_{\text{temp-rp-pe}} = \frac{k_{\max} \cdot U_{\text{m}}}{\sqrt{3}} \tag{4.1}$$

$$U_{\text{temp-rp-pp}} = k_{\text{d}} \cdot U_{\text{m}} \tag{4.2}$$

Where:

- $U_{\text{temp-rp-pe}}$ is the representative phase-to-earth temporary overvoltage. [V]
- $U_{\text{temp-rp-pp}}$ is the representative phase-to-phase temporary overvoltage. [V]
- U_{m} is the highest voltage for equipment. [V]
- $k_{\max}$ is a the maximum value between an earth fault factor and a load rejection factor. A recommended value of $k_{\max} = 1.4$ has been estimated according to [11].
- k_{d} is the load rejection factor. A recommended value of $k_{\text{d}} = 1.4$ has been estimated according to [11].

For voltage systems lower than 36 kV, the maximum phase-to-earth representative overvoltages are caused by earth faults, often reaching the highest voltages for equipment. Regarding phase-to-phase overvoltages, discharge faults are considered as the main overvoltage source.

The representative phase-to-earth and the phase-to-phase overvoltages are calculated using Equation 4.3 and Equation 4.4.

$$U_{\text{temp-rp-pe}} = k \cdot U_{\text{m}} \tag{4.3}$$

$$U_{\text{temp-rp-pp}} = k_{\text{d}} \cdot U_{\text{m}} \tag{4.4}$$

Where:

- $U_{\text{temp-rp-pe}}$ is the representative phase-to-earth temporary overvoltage. [V]
- $U_{\text{temp-rp-pp}}$ is the representative phase-to-phase temporary overvoltage. [V]
- U_{m} is the highest voltage for equipment. [V]
- k is the earth fault factor. A recommended value of $k = 1$ has been estimated according to [11].
- k_{d} is the load rejection factor. A recommended value of $k_{\text{d}} = 1.2$ has been estimated according to [11]

4.3.2 Slow-front overvoltages

In order to calculate the representative slow-front overvoltages, the following procedure has been followed:

Determination of 2% overvoltages

The value of the phase-to-earth overvoltage that has a 2% of probabilities of being exceeded is estimated as the average of the values represented in Figure 4.1. The value that has been selected is $u_{e2} = 2.6$ p.u.

The phase-to-phase overvoltage that has 2% of probabilities of being exceeded is given in Figure 4.2.

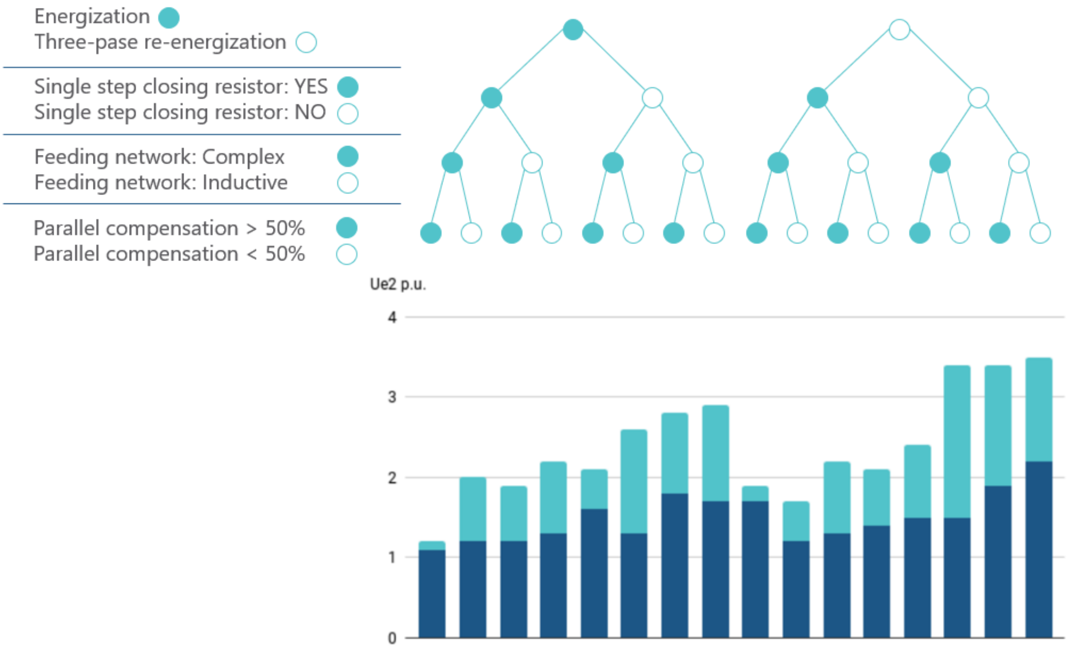

Figure 4.1: Range of 2% slow-front overvoltages at the receiving end due to line energization and re-energization [11]

There are two methods to estimate the representative probability distribution from the 2% overvoltage phase-to-earth value. These are the phase-peak method and the case-peak method. The phase-peak method has been chosen to calculate the truncation values using Equation 4.5 and Equation 4.6:

$$u_{et} = 1.25 \cdot u_{e2} - 0.25 \tag{4.5}$$

$$u_{pt} = 1.25 \cdot u_{p2} - 0.43 \tag{4.6}$$

Where:

- u_{et} is the truncation value of the cumulative distribution of the phase-to-earth overvoltages in p.u
- u_{pt} is the truncation value of the cumulative distribution of the phase-to-phase overvoltages in p.u.
- u_{e2} is the value of the phase-to-earth overvoltage having a 2% of the probability of being exceeded in p.u.
- u_{p2} is the value of the phase-to-phase overvoltage having a 2% of the probability of being exceeded in p.u.

The parts per one are converted to volts following the Equation 4.7

$$U_V = \sqrt{\frac{2}{3}} \cdot U_m \cdot u_{p.u.} \tag{4.7}$$

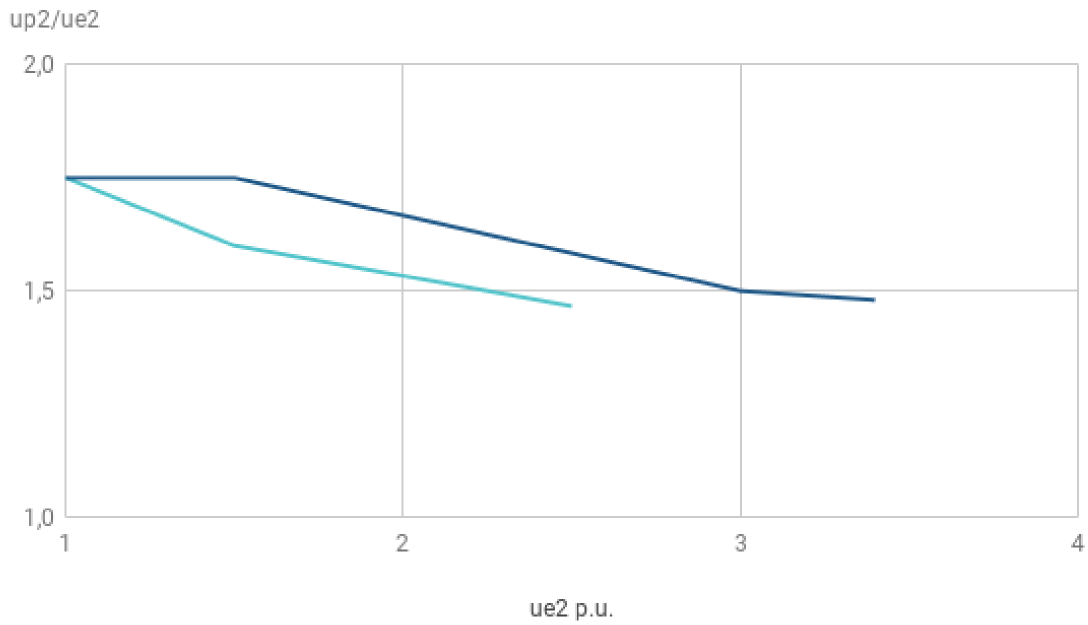

Figure 4.2: Ratio between the 2% values of slow-front overvoltages phase-to-phase and phase-to-earth. The upper part may be applied to three-phase re-energization, the lower part to energization. [11]

Where:

- U_V is an overvoltage. [V]
- U_m is the highest voltage for equipment. [V]
- $u_{p.u}$ is an overvoltage in p.u.

Determination of the switching impulse protective level

As the lightning arrester has been chosen following the process in section 6.3.1, the switching impulse protective level equals U_{ps}.

After computing the probability overvoltages, a comparison between the switching impulse protective level U_{ps} of the lightning arrester and the truncated values of the probability overvoltages is done in order to obtain the representative overvoltages for slow-front impulses. Equation 4.8 and Equation 4.9 are used.

$$U_{\text{sf-rp-pe}} = min\ \left(U_{ps}\,,\ U_{et}\right) \tag{4.8}$$

$$U_{\text{sf-rp-pe}} = min\ \left(2 \cdot U_{ps}\,,\ U_{pt}\right) \tag{4.9}$$

Where:

- $U_{\text{sf rp-pe}}$ is the representative phase-to-earth slow-front overvoltage. [V]
- $U_{\text{sf-rp-pe}}$ is the representative phase-to-phase slow-front overvoltage. [V]
- U_{ps} is the switching impulse protective level of the surge arrester. [V]

- U_{et} is the phase-to-earth truncation overvoltage. [V]
- U_{pt} is the phase-to-phase truncation overvoltage. [V]

4.3.3 Fast-front overvoltages

For fast-front overvoltages, the coordination withstand overvoltages will be directly computed in Subsection 4.4.3, using a simplified empirical formula and a statistical approach that considers the behavior of the lightning overvoltages within the substation.

4.4 Determination of the coordination withstand voltages

According to [11], a deterministic approach will be adopted to determine the coordination overvoltages. This deterministic method consists of applying different factors to the representative overvoltages. In addiction, these factors which vary depending on the shape of the overvoltages, taking into account inaccuracies of the data and performance criteria.

4.4.1 Temporary overvoltages

For the temporary overvoltages, the coordination factor is equal to one. Hence, the representative overvoltages and the coordination overvoltages are equal. The calculation of the phase-to-earth and phase-to-phase temporary overvoltages are represented by Equation 4.10 and Equation 4.11 respectively.

$$U_{\text{temp-cw-pe}} = k_{cd} \cdot U_{\text{temp-rp-pe}} \tag{4.10}$$

$$U_{\text{temp-cw-pp}} = k_{cd} \cdot U_{\text{temp-rp-pp}} \tag{4.11}$$

Where:

- $U_{\text{temp-cw-pe}}$ is the coordination phase-to-earth temporary overvoltage. [V]
- $U_{\text{temp-cw-pp}}$ is the coordination phase-to-phase temporary overvoltage. [V]
- $U_{\text{temp-rp-pe}}$ is the representative phase-to-earth temporary overvoltage. [V]
- $U_{\text{temp-rp-pp}}$ is the representative phase-to-phase temporary overvoltage. [V]
- k_{cd} is the coordination factor that is equal to 1.

4.4.2 Slow-front overvoltages

For this type of overvoltage, a deterministic approach will be used. Therefore, the factor applied will consider possible uncertainties of the lightning arrester protective level that could lead to an increase of the failure rates.

Moreover, the coordination factor for slow-front impulses can be determined considering the relation between the switching impulse protective level U_{ps} and the phase-to-earth and phase-to-phase 2% distribution overvoltages: U_{e2} and U_{p2}. The coordination factor is obtained from Figure 4.3.

The coordination slow-front overvoltages are obtained from Equation 4.12 and Equation 4.13.

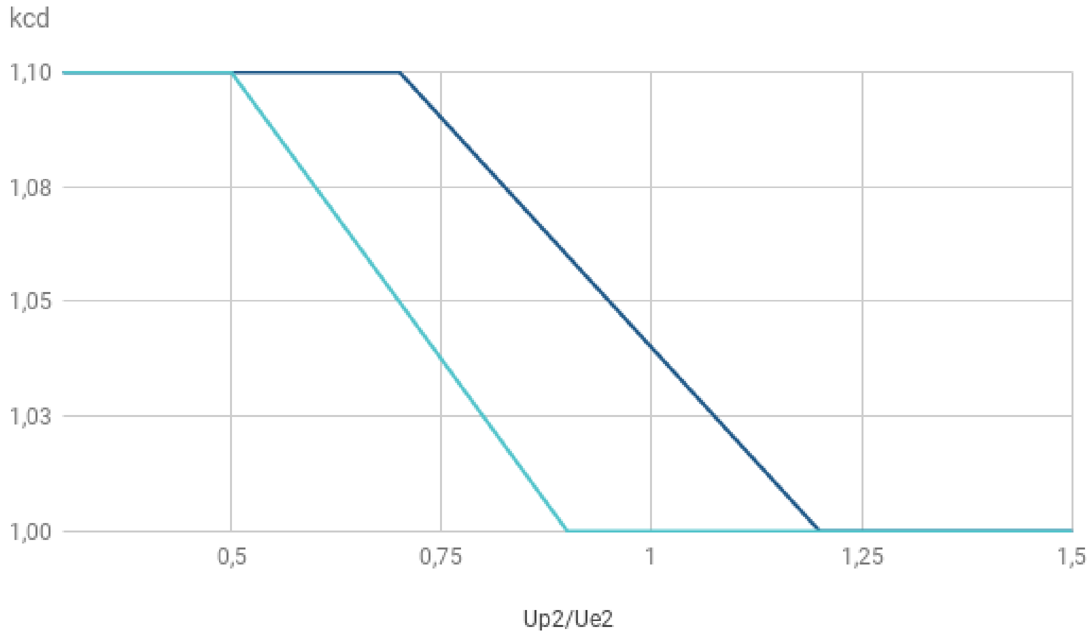

Figure 4.3: Evaluation of deterministic coordination factor k_{cd} [11]

$$U_{\text{sf-cw-pe}} = k_{\text{cd-pe}} \cdot U_{\text{sf-rp-pe}} \tag{4.12}$$

$$U_{\text{sf-cw-pp}} = k_{\text{cd-pp}} \cdot U_{\text{sf-rp-pp}} \tag{4.13}$$

Where:

- $U_{\text{sf-cw-pe}}$ is the coordination phase-to-earth slow-front overvoltage. [V]
- $U_{\text{sf-cw-pp}}$ is the coordination phase-to-phase slow-front overvoltage. [V]
- $U_{\text{sf-rp-pe}}$ is the representative phase-to-earth slow-front overvoltage. [V]
- $U_{\text{sf-rp-pp}}$ is the representative phase-to-phase slow-front overvoltage. [V]
- $k_{\text{cd-pe}}$ is the coordination factor for phase-to-earth voltages.
- $k_{\text{cd-pp}}$ is the coordination factor for phase-to-phase voltages.

4.4.3 Fast-front overvoltages

For fast-front overvoltages, a deterministic coordination factor that is equal to 1 is applied, k_{cd} = 1. This value was chosen due to some probability effects are included int the calculation of the coordination overvoltages. These probability effects can be estimated by using a statistical method, which considers the effects of the overhead lines at the entrance of the substation.

The coordination overvoltages for fast-front impulses proceed as given in Equation 4.14.

$$U_{\text{ff-cw}} = U_{\text{pl}} + \frac{A \cdot f_s}{N} \cdot \frac{L_t}{L_{sp} + L_f} \tag{4.14}$$

Where:

- $U_{\text{ff-cw}}$ is the coordination lightning impulse withstand overvoltage. [V]
- U_{pl} is the lightning impulse protective level of the surge arrester. [V]
- A is the voltage that describes the performance of the lines connected to the substation. [V]
- f_s is a steepness reduction factor that is equal to 0.5.
- N is the number of overhead lines, which leave to the substation. $N = 1$ is taken as a conservative value. [V]
- L_t is the separation distance from the lightning arrester to the protected device. [m]
- L_{sp} is the span length. [m]
- L_f is the length of the overhead line. It is an estimation based on the acceptable failure rate and the line outage rate. [m]

The length of the overhead line is calculated using Equation 4.15

$$L_f = \frac{R_a}{R_{km}} \tag{4.15}$$

Where:

- L_f is the length of the overhead line. [m]
- R_a is the acceptable failure rate. [1/year]
- R_{km} is the overhead line outage rate. [1/(m.year)]

According to [14], the values for these parameters can be found in Table 4.3.

Table 4.3: Example for protective zone for air-insulated substations. [14]

Higest voltage [kV]	A [kV]	f_s	N	L_t [m]	L_{sp} [m]	R_a [1/year]	R_{km} [1/m.year]
36	2700	0.5	1	3	100	0.25 %	0.006 %
100	2700	0.5	1	15	200	0.25 %	0.001 %
245	4500	0.5	1	30	300	0.25 %	0.001 %
420	7000	0.5	1	30	300	0.25 %	0.001 %
800	11000	0.5	1	40	400	0.2 %	0.00015 %

Determination of the lightning impulse protective level

As the lightning arrester has been presented in section 6.3.1, the lightning impulse protective level is obtained depending on the nominal discharge current of the lightning arrester.

For nominal currents $I_{nom} = 10$ kA and $I_{nom} = 20$ kA, the corresponding lightning impulse protective levels are $U_{pl} = U_{\text{pl-10kA}}$ and $U_{pl} = U_{\text{pl-20kA}}$ respectively.

4.5 Determination of the required withstand voltages

The required withstand voltages, which have to be verified during the lifetime of the equipment, take into account two correction factors. A safety factor that represents the difference of the insulation behavior during operation conditions and test conditions, and a correction factor that considers atmospheric conditions.

The safety correction factors that are applied to each kind of overvoltage: temporary, slow-front and fast-front, are given in Equation 4.16 and Equation 4.17 respectively.

$$K_{si} = 1.15 \tag{4.16}$$

$$K_{se} = 1.05 \tag{4.17}$$

Where:

- K_{si} is the safety correction factor for the internal insulation.
- K_{se} is the safety correction factor for the external insulation.

The atmospheric effect is based on the air pressure's dependence on the altitude. This factor's measurement is applied to measure the differences in the air dielectric strength as the altitude increases. Moreover, the atmospheric correction factor can be calculated using Equation 4.18.

$$K_a = \exp\left(m \cdot \frac{H}{8150}\right) \tag{4.18}$$

Where:

- K_a is the atmospheric correction factor.
- H is the altitude above the sea level. [m]
- m is a coefficient.

The coefficient m may vary depending on the overvoltage.

- $m = 0.5$ for temporary overvoltages.
- m is defined according to Figure 4.4 for slow-front overvoltages.
- $m = 1$ for fast-front overvoltages.

The results are a set of required withstand voltages for external and internal insulation and for phase-to-earth and phase-to-phase voltages. They are given by Equation 4.19

$$U_{rw} = K_a \cdot K_s \cdot U_{cw} \tag{4.19}$$

Where:

- U_{rw} is the required overvoltage. [V]
- U_{cw} is the coordination overvoltage. [V]
- K_a is the atmospheric correction factor. Note that for switching impulses, there are different atmospheric correction factors depending on phase-to-earth or phase-to-phase conditions.
- K_s is the safety correction coefficient for internal K_{si} or external K_{se} insulation.

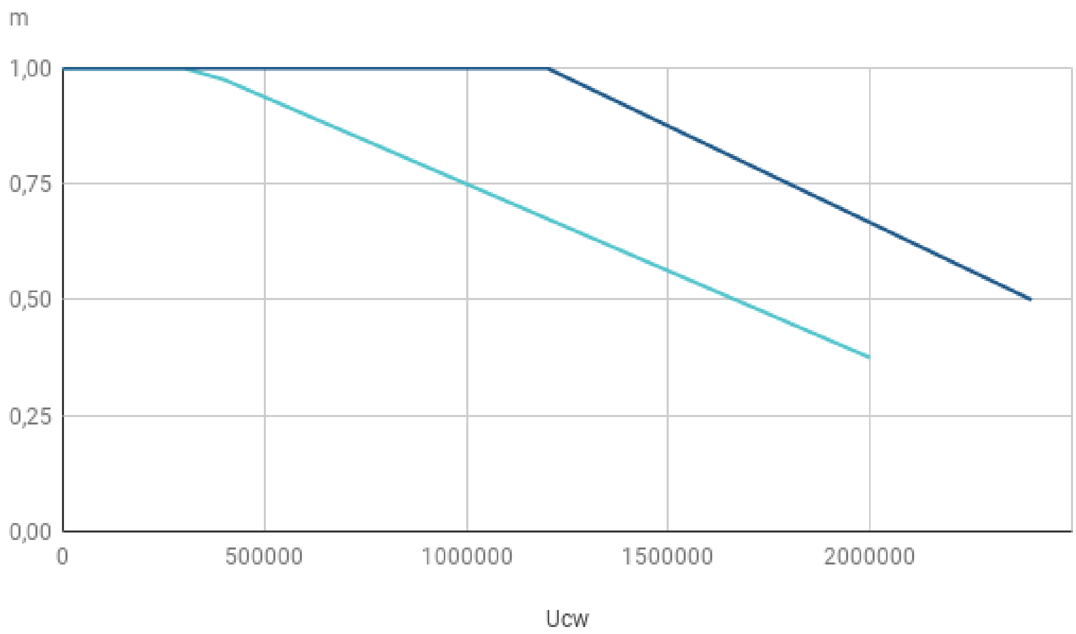

Figure 4.4: Dependence of exponent m on the coordination switching impulse withstand voltage [11]

4.6 Conversion to rated withstand voltages

For class I, the standard rated withstand voltages include the short duration power frequency withstand voltages (temporary overvoltages) and the lightning impulse withstand voltages (fast-front overvoltages). For class II, the standard rated withstand voltages include both the switching (slow-front overvoltages) and the lightning impulse withstand voltages (fast-front overvoltages).

According to class I, the switching impulse withstand voltages are converted to short duration power frequency withstand voltages and to lightning impulse withstand voltages by applying the factors given in Table 4.4

Table 4.4: Test conversion factors for range I, to convert required switching impulses withstand voltages to short-duration power-frequency and lightning impulse withstand voltages [11]

Insulation type	Short duration power frequency withstand voltages	Lightning impulse Withstand voltage
External Insulation: Clean and Dry Insulation phase-to-earth	$0.6 + \frac{U_{rw}}{8500000}$	$1.05 + \frac{U_{rw}}{6000000}$
External Insulation: Clean and Dry Insulation phase-to-phase	$0.6 + \frac{U_{rw}}{12700000}$	$1.05 + \frac{U_{rw}}{9000000}$
Internal Insulation: Liquid-immersed Insulation	0.5	1.1

The same principle applies to class II where the short-duration power frequency withstand voltages are converted to switching impulse withstand voltages. In this case, the considered factors are given in Table 4.5

Table 4.5: Test conversion factors for range II, to convert required short-duration power-frequency withstand voltages to switching impulse withstand voltages [11]

Insulation type	Switching impulse Withstand voltage
External Insulation Clean: and Dry Insulation	1.4
Internal Insulation: Liquid-immersed Insulation	2.3

4.7 Selection of the rated insulation levels according to IEC

After the calculation of the three main overvoltages and the conversion of some of them, the result is a set of overvoltages. However, in order to obtain the withstand voltages that are recommended for the standard, the maximum values will be considered.

The standard withstand voltages for class I substation can be found in Table 4.6. For class II substations, the reference values are presented in Table 4.7.

The withstand voltages are necessary to obtain the minimum phase-to-earth and phase-to-phase clearance distances. The clearance distances are required to establish the minimum safety distances between the elements of the substation.

Table 4.6: Standard insulation levels for range I [9]

Highest Voltage for equipment [kV]	Standard rated short duration power frequency withstand voltages [kV]	Standard rated lightning impulse withstand voltage [kV]
3.6	10	20 40
7.2	20	40 60
12	28	60 75 95
17.5	38	75 95
24	50	95 125 145
36	70	145 170
52	95	250
72.5	140	325
100	150	380 450
123	185 230	450 550
145	185 230 275	450 550 650
170	230 275 325	550 650 750
245	275 325 360 395 460	650 750 850 950 1050

Table 4.7: Standard insulation levels for range II [9]

Highest Voltage for equipment [kV]	Standard rated lightning impulse withstand voltage phase-to-earth [kV]	Standard rated lightning impulse withstand voltage phase-to-phase [kV]	Standard rated lightning impulse withstand voltage[kV]
300	750	1125	850 950
	850	1275	950 1050
362	850	1360	950 1050
	950	1425	1050 1175
420	850	1575	1050 1175
	950	1615	1175 1300
	1050	1680	1300 1425
550	950	1615	1175 1300
	1050	1680	1300 1425
	1175	1763	1425 1550
800	1300	2210	1675 1800
	1425	2423	1800 1950
	1550	2480	1950 2100
1100	1550	2423	2100 2250
	1675	2764	2250 2400
	1800	2880	2400 2550
1200	1675	2848	2100 2250
	1800	2970	2250 2400
	1950	3120	2550 2700

4.8 Selection of the clearance distances according to IEC

The objective of the insulation coordination's calculation is to determine the minimum phase-to-earth and phase-to-phase clearances. The minimum clearances define the minimum distances to comply with the insulation coordination requirements. For safety conditions, some additional distances given in Chapter 5 will be added to the clearance distances.

The tables 4.8, 4.9, and 4.10 present the minimum clearances that ensure the specifications of the insulation coordination.

Table 4.8 associates the standard rated lightning impulse withstand voltages for the substation of class I with the minimum air clearances for rod-structure and conductor-structure configurations. Moreover, Table 4.9 links the standard rated switching impulse withstand voltages phase-to-earth with the minimum air clearances for the conductor-structure and the rod-structure configurations. Finally, Table 4.10 correlates the air clearances with the standard rated switching impulse withstand voltages phase-to-phase for the conductor-conductor and rod-conductor configurations.

Table 4.8: Correlation between standard rated lightning impulse withstand voltages and minimum air clearances for class I [9], [10]

Standard rated lightning impulse withstand voltage [kV]	Minimum clearance [mm] Rod-structure	Minimum clearance [mm] Conductor-structure
20	60	
40	60	
60	90	
75	120	
95	160	
125	220	
145	270	
170	320	
200	380	
250	480	
325	630	
380	750	
450	900	
550	1100	
650	1300	
750	1500	
850	1700	1600
950	1900	1700
1050	2100	1900
1175	2350	2200
1300	1600	2400
1425	2850	2600
1550	3100	2900
1675	3350	3100
1800	3600	3300
1950	3900	3600
2100	4200	3900
2250	4500	4150
2400	4800	4450
2550	5100	4700
2700	5400	5000

Table 4.9: Correlation between standard rated switching impulse withstand voltages and minimum phase-to-earth air clearances [9], [10]

Standard rated switching withstand voltage [kV]	Minimum phase-to-earth [mm]	
	Rod-structure	Conductor-structure
750	1900	1600
850	2400	1800
950	2900	2200
1050	3400	2600
1175	4100	3100
1300	4800	3600
1425	5600	4200
1550	6400	4900
1675	7400	5600
1800	8300	6300
1950	9500	7200

Table 4.10: Correlation between standard rated switching impulse withstand voltages and minimum phase-to-phase air clearances for class II [9], [10]

Standard rated switching withstand voltage [kV]	Minimum phase to parth [mm]	
	Conductor-conductor parallel	Rod-conductor
1125	2300	2600
1275	2600	3100
1360	2900	3400
1425	3100	3600
1575	3600	4200
1615	3700	4300
1680	3900	4600
1763	4200	5000
2210	6100	7400
2423	7200	9000
2480	7600	9400
2635	8400	10000
2764	9100	10900
2848	9600	11400
2880	9800	11600
2970	10300	12300
3120	11200	13300

For class I systems, the phase-to-earth and phase-to-phase air distances are calculated using Equation 4.20 and Equation 4.21.

$$d_{\text{pe}} = min\left(d_{\text{rod-str}} , \ d_{\text{cond-str}} \right) \tag{4.20}$$

Where:

- d_{pe} is the phase-to-earth air distance. [m]
- $d_{rod\text{-}str}$ is the rod-structure minimum clearance. [m]
- $d_{cond\text{-}str}$ is the conductor-structure minimum clearance. [m]

$$d_{pp} = d_{rod\text{-}str} \tag{4.21}$$

Where:

- d_{pp} is the phase-to-phase air distance. [m]
- $d_{rod\text{-}str}$ is the rod-structure minimum clearance. [m]

For class II substations, the phase-to-earth and phase-to-phase air distances are calculated using Equation 4.22 and Equation 4.23.

$$d_{pe} = max\left(d_{rod\text{-}str\text{-}switching}\,,\ d_{rod\text{-}str\text{-}lightning}\right) \tag{4.22}$$

Where:

- d_{pe} is the phase-to-earth air distance. [m]
- $d_{rod\text{-}str\text{-}switching}$ is the rod-structure minimum clearance for rated switching withstand impulses. [m]
- $d_{rod\text{-}str\text{-}lightning}$ is the rod-structure minimum clearance for rated lightning withstand impulses. [m]

$$d_{pp} = max\left(d_{conductor\text{-}str\text{-}switching}\,,\ d_{rod\text{-}str\text{-}lightning}\right) \tag{4.23}$$

Where:

- d_{pp} is the phase-to-phase air distance. [m]
- $d_{conductor\text{-}str\text{-}switching}$ is the conductor-structure minimum clearance for the maximum rated switching withstand impulses. [m]
- $d_{rod\text{-}str\text{-}lightning}$ is the rod-structure minimum clearance for the maximum rated lightning withstand impulses. [m]

4.9 Determination of the temporary, BIL and BSL voltages according to the IEEE

The IEEE standard follows a different procedure in calculating the overvoltages and determining the clearance distances for the two substation classes (I and II). The processes used to calculate the temporary, the basic lightning, and the basic switching voltages are presented in the following subsections.

4.9.1 Determination of the temporary voltages:

For substation of class I as depicted in Table 4.2, the temporary voltages are calculated based on the IEC approach considering the load rejection factors and the atmospheric factor for both phase-earth and phase-phase configurations.

The temporary voltages for phase-earth and phase-phase are calculated using Equation 4.24 and Equation 4.25.

$$U_{\text{temp-pe}} = \frac{k_{\text{max}} \cdot U_{\text{m}}}{K_{\text{a}}} \tag{4.24}$$

$$U_{\text{temp-pp}} = \frac{k_{\text{max}} \cdot U_{\text{m}}}{K_{\text{a}}} \tag{4.25}$$

Where:

- $U_{\text{temp-pe}}$ is the phase-to-earth temporary overvoltage. [V]
- $U_{\text{temp-pp}}$ is the phase-to-phase temporary overvoltage. [V]
- U_{m} is the maximum voltage for equipment. [V]
- k_{max} is a the maximum value between an earth fault factor and a load rejection factor. A recommended value of $k_{\text{max}} = 1.4$ has been estimated according to [11].
- k_{a} is the atmospheric factor. It is calculated according to Equation 4.26.

$$\delta = \exp\left(\frac{-H}{8.9}\right) \tag{4.26}$$

Where:

- δ is the atmospheric factor.
- H is the altitude above the sea level. [m]

4.9.2 Determination of the basic lightening impulse voltage BIL:

The basic lightning impulse level BIL is determined for both substation classes I and II and only for the phase-to-earth configuration, with the existence of a surge arrester, the BIL is calculated following Equation 4.27.

$$BIL = \frac{U_{\text{pl}}}{k_{\text{a}}} \tag{4.27}$$

Where:

- BIL is the Basic lightning impulse level. [kV]
- U_{pl} is the lightning impulse protective level of the surge arrester. [V]
- k_{a} is the atmospheric factor. The factor is calculated using Equation 4.26.

As the lightning arrester has been presented in section 6.3.1, the lightning impulse protective level is obtained depending on the nominal discharge current of the lightning arrester.

For nominal currents $I_{\text{nom}} = 10$ kA and $I_{\text{nom}} = 20$ kA, the corresponding lightning impulse protective levels are $U_{\text{pl}} = U_{\text{pl-10kA}}$ and $U_{\text{pl}} = U_{\text{pl-20kA}}$ respectively.

4.9.3 Determination of the basic switching impulse voltage BSL:

The basic switching impulse voltage BSL is calculated for the substation class II and for the phase-to-earth and phase-to-phase configurations. The calculations considers a number of insulations in parallel between 5 and 10 lines. To calculate the BSL, several parameters must be defined through the following procedures.

Determination of the strength-to-stress ratio:

The first parameter that must be defined in the calculation of the BSL is the strength-to-stress ratio which represents a ratio between the statistical switching overvoltage and the statistical withstand voltage. The statistical switching overvoltage depicts the minimum insulation strength required and it is defined as E_2 for the phase-to-earth and the stress E_{2z} for the phase-to-phase insulation. As for the statistical withstand voltage, it is the maximum surge voltage applied to the equipment and it is defined as V_3 for the phase-to-earth and V_{30} for the phase-to-phase insulation.

The determination of the ratio depends on the switching surge flashover rate (SSFOR) that represents the number of flashover per number of applied switching. Therefore, for a giving SSFOR, a strength-to-stress ratio is determined; in the presented calculation considering a self-restoring insulation, an SSFOR of 1/100 was chosen.

Based on [12] considering a 1/100 flashover rate and the use of a surge arrester, the ratio that has been selected for phase-to-earth insulation is $V_3/E_2 = 0.96$ p.u and for the phase-to-phase is $V_{30}/E_{2z} = 0.94$ p.u.

Determination of the statistical switching overvoltage:

The switching overvoltages are statistically analyzed to obtain a probability of 2% of being exceeded and this value is the statistical withstand voltage E_2 for the phase-to-earth and the stress E_{2z} for the phase-to-phase insulation.

With the SSFOR of 1/100 chosen and according to [12] the value that has been selected for the phase-to-earth is $E_2 = 2.59$ p.u .

On the other hand, the value of the stress E_{2z} is determined from the ratio of the phase-to-phase statistical switching overvoltages E_{2z}/E_2. In addition, this ratio is determined according to [12]; because the E_{2z} values vary between the range of 2 p.u and 3 p.u and the E_{2z}/E_2 ratio varies between 1.3 p.u and 3 p.u; therefore, the value that has been selected for the ratio is $E_{2z}/E_2 = 1.55 p.u.$ Moreover, the value of E_2 is kept as 2.59 p.u; hence, E_{2z} can then be calculated from the Equation 4.28

$$E_{2z} = E_2 \cdot 1.55 \tag{4.28}$$

Where:

- E_{2z} is the stress. [p.u]
- E_2 is the statistical switching overvoltage considered as 2.59. [p.u]

As all the voltage are per unit, they are converted to volts following the Equation 4.7.

Determination of the coefficient of variation σ_f/CFO:

The strength of the insulation is characterized by two main parameters which are the coefficient of variation σ_f/CFO and the critical flashover voltage CFO. for a switching surge flashover rate SSFOR = 1/100, and based on [12] the coefficient of variation is assumed to be 0.07 for the phase-to-earth insulation and 0.035 for the phase-to-phase insulation.

Determination of the critical flashover voltage *CFO*:

As we mentioned above, the strength of the insulation is characterized by two parameters and one of them is the critical flashover voltage CFO that corresponds to the 50% probability of flashover for a single impulse application. The CFO for the phase-to-earth and phase-to-phase are calculated using Equation 4.29 and Equation 4.30 respectively.

$$CFO_{\mathrm{pe}} = \frac{V_3}{1 - 3 \cdot \frac{\sigma_f}{CFO}} \tag{4.29}$$

Where:

- CFO_{pe} is the critical flashover voltage for the phase-to-earth insulation. [kV/m]
- V_3 is the statistical withstand voltage. [kV]
- $sigma_f$ is the variation coefficient that is equal to 0.07.

$$CFO_{\mathrm{pp}} = \frac{V_{30}}{1 - 3 \cdot \frac{\sigma_f}{CFO}} \tag{4.30}$$

Where:

- CFO_{pp} is the critical flashover voltage for the phase-to-earth insulation. [kV/m]
- V_{30} is the statistical withstand voltage. [kV]
- $sigma_f$ is the variation coefficient that is equal to 0.035.

After determining all the parameters discussed above, based on [13] the BSL phase-to-earth and phase-to-phase are calculated using the Equation 4.31 and Equation 4.32 respectively.

$$BSL_{\mathrm{pe}} = M_{\mathrm{pe}} \cdot CFO_{\mathrm{pe}} \tag{4.31}$$

Where:

- BSLpe is the phase-to-earth Basic lightning impulse level. [kV]
- M_{pe} is the phase-to-earth multiplier factor, it equals to 0.9104.
- CFO_{pe} is the critical flashover voltage for the phase-to-earth insulation. [kV/m]

$$BSL_{pp} = M_{pp} \cdot CFO_{pp} \tag{4.32}$$

Where:

- BSLpp is the phase-to-phase Basic lightning impulse level. [kV]
- M_{pp} is the phase-to-phase multiplier factor, it equals to 0.955.
- CFO_{pp} is the critical flashover voltage for the phase-to-phase insulation. [kV/m]

4.10 Selection of the rated insulation levels according to IEEE

After the calculation of the temporary, BIL, and BSL overvoltages, the standard recommended withstand voltages must be obtained by considering the maximum values.

The standard withstand voltages for class I substation can be found in Table 4.11. As for class II substations, the reference values are presented in Table 4.12.

The withstand voltages are necessary to obtain the minimum phase-to-earth and phase-to-phase clearance distances. Those distances are significant to establish the minimum safety distances between the elements of the substation.

Table 4.12: Standard insulation levels for class II [13]

Highest Voltage for equipment [kV]	Standard rated lightning impulse withstand voltage BIL [kV]	Standard rated switching impulse withstand voltage BSL [kV]
362	900	650
	975	750
	1050	825
	1175	900
	1300	975
		1050
550	1300	1175
	1425	1300
	1550	1425
	1675	1550
	1800	
800	1800	1300
	1925	1425
	2050	1550
		1675
		1800

Table 4.11: Standard insulation levels for class I [13]

Highest Voltage for equipment [kV]	Standard rated low frequency, short duration power frequency withstand voltages [kV]	Standard rated lightning impulse withstand voltage BIL [kV]
1.2		30 45
5		60 75
15	34	95 110
26.2	50	150
36.2	70	200
48.3	95	250
72.5	95 140	250 350
121	140 185 230	350 450 550
145	185 230 275	450 550 650
169	230 275 325	550 650 750
242	275 325 360 395 480	650 750 825 900 975 1050

4.11 Calculation of the clearance distances according to IEEE

As mentioned in 4.8, the objective of the insulation coordination's calculation is to determine the minimum phase-to-earth and phase-to-phase clearances and the withstand voltages are very important to calculate those clearances.

On one hand, for the substation class I, the phase-to-earth clearance distance is calculated based on the basic impulse lightening voltage following Equation 4.33. Moreover, the standard minimum clearances presented in IEEE are based on a CFO value of 605 kV/m, a value which has been found to represent the typical geometry for an air-insulated substation.

$$S_{\text{pe}} = \frac{c \cdot BIL}{CFO} \tag{4.33}$$

Where:

- S_{pe} is the phase-to-earth clearance distance. [m]

- BIL is the basic impulse lightening voltage. [kV]
- c is the protective margin, which equals to 1.15.
- CFO is the critical flashover voltage, that us equal to 605. [kV/m]

Based on [13], the phase-to-phase clearance distance is calculated following Equation 4.34.

$$S_{pp} = 1.1 \cdot S_{pe} \tag{4.34}$$

Where:

- S_{pp} is the phase-to-phase clearance distance. [m]
- S_{pe} is the phase-to-earth clearance distance. [m]

On the other hand, for substations of class II, few parameters must be determined for the calculation of the clearance distances.

The first parameter to be defined is the gap factor, in [12] typical gap factors for phase-to-earth and phase-to-phase insulation are presented; hence, the gap factor considered is for the horizontal rod-rod configuration with a value of $K_g = 1.35$ for both insulations.

The other parameter is the re-calculated CFO after the selection of the standard BSL; in this case, the CFO is calculated following Equation 4.35 and Equation 4.36 for phase-to-earth and phase-to-phase insulation respectively.

$$CFO_{\text{re-pe}} = \frac{BSL_{upe}}{f_{pe}} \tag{4.35}$$

Where:

- $CFO_{\text{re-pe}}$ is the recalculated CFO. [kV/m]
- BSL_{upe} is the selected standard BSL for phase-to-earth. [kV]
- f_{pe} is the multiplier factor for the phase-to-earth, which is equal to 0.9104.

$$CFO_{\text{re-pp}} = \frac{BSL_{upp}}{f_{pp}} \tag{4.36}$$

Where:

- $CFO_{\text{re-pp}}$ is the recalculated CFO. [kV/m]
- BSL_{upp} is the selected standard BSL for phase-to-phase. [kV]
- f_{pp} is the multiplier factor for the phase-to-phase, which is equal to 0.955.

Moreover, the atmospheric correction factor is taken into consideration when the substation is above sea level. The correction factor is calculated using Equation 4.37.

$$\delta^{m} = \exp\left(\frac{-H\dot{m}}{8.9}\right) \tag{4.37}$$

Where:

- δ^{m} is the atmospheric correction factor.
- H is the altitude above the sea level. [m]
- m is the correction factor, it is assumed to be 0.5.

Having the re-calculated CFO, the gap factor, and the atmospheric correction factor, the clearance distances are calculated based on the basic impulse switching voltage following Equation 4.38 and Equation 4.39 for phase-to-earth and phase-to-phase respectively.

$$S_{\mathrm{pe}} = \frac{8}{\frac{(3400K_{\mathrm{g}}\delta^{\mathrm{m}})}{CFO_{\text{re-pe}}} - 1} \tag{4.38}$$

Where:

- S_{pe} is the phase-to-earth clearance distance. [m]
- δ^{m} is the atmospheric correction factor.
- K_{g} is the gap factor.
- $CFO_{\text{re-pe}}$ is the recalculated critical flashover voltage. [kV/m]

$$S_{\mathrm{pp}} = \frac{8}{\frac{(3400K_{\mathrm{g}}\delta^{\mathrm{m}})}{CFO_{\text{re-pp}}} - 1} \tag{4.39}$$

Where:

- S_{pp} is the phase-to-phase clearance distance. [m]
- δ^{m} is the atmospheric correction factor.
- K_{g} is the gap factor.
- $CFO_{\text{re-pp}}$ is the recalculated critical flashover voltage. [kV/m]

4.12 Selection of the clearance distances according to IEEE

After the calculation of the clearance distances for the two classes of the substation based on both the basic lightening impulse and basic switching impulse voltages, the minimum clearances that ensure the specifications of the insulation coordination are determined based on recommended values from the IEEE. The standard values that are associated with the standard rated lightning impulse withstand voltages BIL for the substation of class I and II are presented in Table 4.13. As for the standard values that are associated with the standard rated switching impulse withstand voltages BSL for the substation of class II are presented in Table 4.14

Table 4.13: Correlation between standard rated lightning impulse withstand voltages and minimum air clearances for class I and II [13]

Standard rated lightning impulse withstand voltage BIL [kV]	Minimum clearance [mm]	
	phase-earth	phase-phase
30	57	63
45	86	95
60	115	125
75	145	155
95	180	200
110	210	230
150	285	315
200	380	420
250	475	525
350	665	730
450	855	940
550	1045	1150
650	1235	1360
750	1325	1570
825	1570	1725
900	1710	1880
975	1855	2040
1050	2000	2200
1175	2235	2455
1300	2470	2720
1425	2710	2980
1550	2950	3240
1675	3185	3500
1800	3420	3765
1925	3660	4025
2050	3900	4285
2300	4375	4815

Table 4.14: Correlation between standard rated switching impulse withstand voltages and minimum air clearances for class II [13]

Standard rated lightning impulse withstand voltage BSL [kV]	Minimum clearance [mm]	
	phase-earth	phase-phase
550	1265	1630
650	1540	2000
750	1835	2405
825	2065	2725
900	2305	3065
975	2560	3505
1050	2825	3905
1175	3300	4640
1300	3820	5475
1425	4385	6420
1550	5010	7840
1675	5705	9200
1800	6475	10815

Finally, once the standard phase-to-earth and phase-to-phase clearance distances based on the BSL and BIL voltages are selected, the adopted phase-to-earth and phase-to-phase distances will be the maximum selected ones; determined following Equation 4.40 and Equation 4.41.

$$S_{\text{pe}} = max\left(S_{\text{pe-lightening}}, S_{\text{pe-switching}}\right) \tag{4.40}$$

Where:

- S_{pe} is the phase-to-earth air distance. [m]
- $S_{\text{pe-switching}}$ is the phase-to-earth minimum clearance for rated switching withstand impulses. [m]
- $S_{\text{pe-lightening}}$ is the phase-to-earth minimum clearance for rated lightning withstand impulses. [m]

$$S_{\text{pp}} = max\left(S_{\text{pp-lightening}}, S_{\text{pp-switching}}\right) \tag{4.41}$$

Where:

- S_{pp} is the phase-to-phase air distance. [m]
- $S_{\text{pp-switching}}$ is the phase-to-phase minimum clearance for rated switching withstand impulses. [m]
- $S_{\text{pp-lightening}}$ is the phase-to-phase minimum clearance for rated lightning withstand impulses. [m]

Chapter 5

Safety Distances

In this chapter, the safety distances within the substation will be defined and derived from the phase-to-earth and phase-to-phase distances calculated in Chapter 4. These safety distances will be presented as the minimum distance between the elements located at the substation. A method according to [15] will be followed for the calculation; however, there may be discrepancies between the concerned utility and the general model presented due to specific or local conditions or procedures established by the local standards.

5.1 Introduction

There are different methods to determine the safety distances between the elements of a substation. These safety distances may vary depending on the utility due to the particularity of each national operating voltages. In this chapter, a generic model to compute the safety clearances is presented according to [15]. The method of application takes into account not only the voltage levels but also the operating conditions of the equipment as well as a factor that considers the movement of the staff in all three dimensions.

The safety distance is the minimum distance that should be maintained between a live part of the conductor and the earth or another piece of the equipment. The safety distance is the sum of two values: a basic value and a factor that considers the movement of the staff during maintenance, as shown in Figure 5.1.

- The basic value represents the limit of the danger zone for electrical disturbances and it is related to the impulse withstand voltage. Depending on the value of this voltage, a safety coefficient will be applied to the phase-to-earth clearance that is obtained in Section 4.8.
- The other factor defines a safety zone and it is a function of the movements made by the operators during maintenance. The safety zone determines a zero electrical risk zone for the authorized personnel.

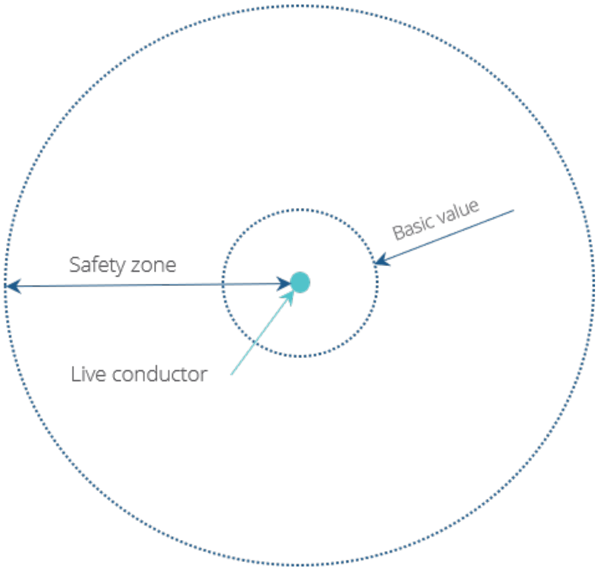

Figure 5.1: The safety distance is made up of two values: basic value and safety zone for staff. Source: Own elaboration from the data provided by [15].

5.2 General procedure for the calculation of the safety distances

In this section, the general procedure given in [15] will be presented. The results that are obtained from this method can be considered conservative for some projects, but they can be considered as a guideline. The following example clarifies the process of determining the safety distances for an air insulated substation. The information required are:

- The voltage level. [V]
- The phase-to-earth clearance distances obtained in Section 4.8. [m]
- The phase-to-phase clearance distances obtained in Section 4.8. [m]
- The impulse withstand voltage of the system given by Section 4.7. [V]

The substation dimensions that came out of this study are the following ones, presented in Figure 5.2:

<u>The dimensions of the switchgear</u>

- The height of the switchgear. This is the first height level of the substation.
- The distance between devices in the bay direction.
- The distance between the conductors.

<u>The dimensions of the busbars</u>

- The height of the busbar. This is the second height level of the substation.
- The distance between the conductors.
- The busbar span.

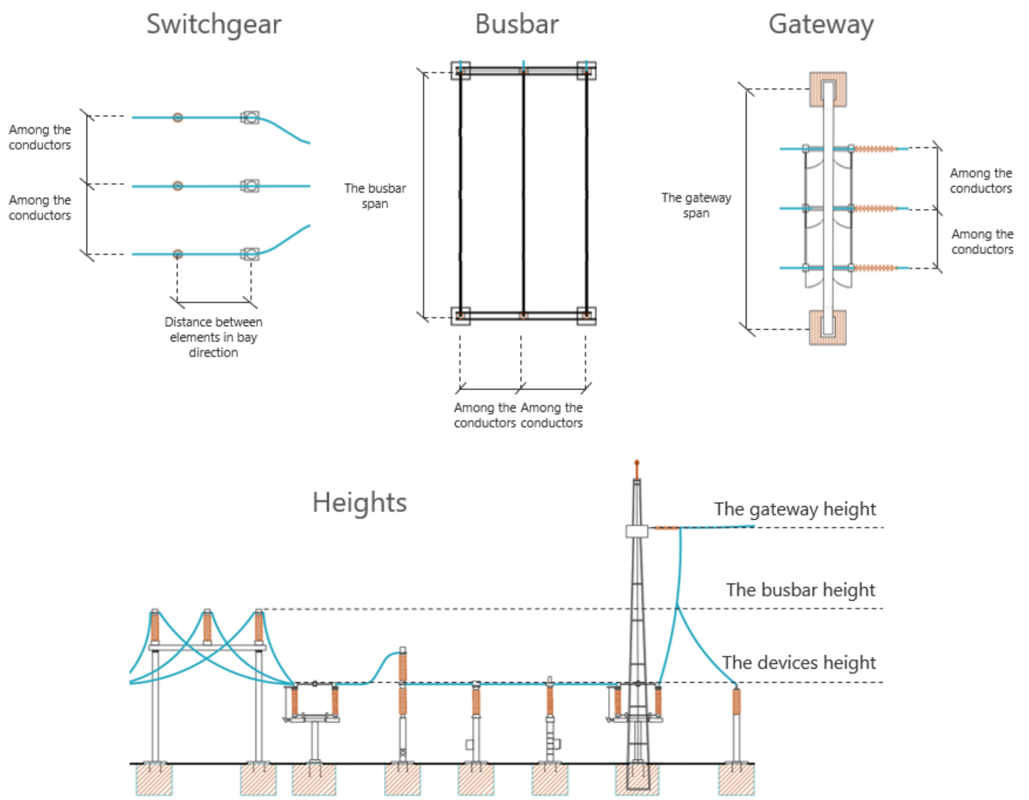

Figure 5.2: The safety distance in the substation field. Source: Own elaboration.

The dimensions of the gateway

- The height of the gateway. This is the third height level of the substation.
- The distance between the conductors.
- The gateway span.

5.2.1 Staff movement factor

There are three dimensions regarding the movement of staff that are contemplated. They correspond to:

- The average height of a worker with his arms raised all the way up and that is equivalent to H_r = 2.25 m.
- The average length of a worker with his arms outstretched, that is L_o = 1.75 m.
- The average height of a worker with his arms raised to a work of plane, that is H_{rw} =1.25 m.

5.2.2 The basic value

The basic value depends on the impulse withstand voltage and it is calculated using Equation 5.1:

$$d_{bv} = f_{bv} \cdot d_{pe} \tag{5.1}$$

Where:

- d_{bv} is the basic value. [m]
- f_{bv} is a factor that corresponds to 1.1 if the impulse withstand voltage $\leq$ 1425 kV and 1.06 if it is $>$ 1425 kV.
- d_{pe} is the phase-to-earth clearance distance. [m]

5.2.3 Field height

There are three height limits for an air insulated substation that are given by Equation 5.2, Equation 5.3, and Equation 5.4.

$$h_{\text{device}} = d_{\text{bv}} + H_{\text{r}} \tag{5.2}$$

Where:

- h_{device} is the first level limit. [m]
- $d_{\text{bv}} + H_{\text{r}}$ is the sum of the basic value and the staff movement factor, it should always be higher than 3 m. [m]

$$h_{\text{busbar}} = h_{\text{device}} + d_{\text{bv}} + H_{\text{rw}} \tag{5.3}$$

Where:

- h_{busbar} is the second level limit. [m]
- h_{device} is the first level limit. [m]
- $d_{\text{bv}} + H_{\text{rw}}$ is the sum of the basic value and the staff movement factor, it should always be higher than 3 m. [m]

$$h_{\text{overhead line}} = h_{\text{busbar}} + d_{\text{bv}} + H_{\text{rw}} \tag{5.4}$$

Where:

- $h_{\text{overhead line}}$ is the third level limit. [m]
- h_{busbar} is the second level limit. [m]
- $d_{\text{bv}} + H_{\text{rw}}$ is the sum of the basic value and the staff movement factor, it should always be higher than 3 m. [m]

5.2.4 Field length

The field length is the total length of the substation and it is defined as the sum of all the distances between the installed switchgear.

An estimation of the safety distance from the extreme position that the live equipment or conductor may occupy to the edge of the following equipment is derived from the same principle represented in Equation 5.5. However, this safety zone value should never be lower than 3.0 m.

$$l_{\text{device}} = max(d_{\text{bv}} + L_{\text{o}}\,,\, d_{\text{pp}}) \tag{5.5}$$

Where:

- l_{device} is the distance between devices in the bay direction.. [m]
- $d_{\text{bv}} + L_{\text{o}}$ is the sum of the basic value and the staff movement factor, it should always be higher than 3 m. [m]
- d_{pp} is the phase-to-phase clearance distance. [m]

5.2.5 Distance between buses

An estimation of the safety distance measured from a bus to another is defined using Equation 5.6. This safety zone should never be lower than 3.0 m.

$$d_{\text{bus}} = max(d_{\text{bv}} + L_{\text{o}}\,,\, d_{\text{pp}}) \tag{5.6}$$

Where:

- d_{bus} is the distance between the conductors. [m]
- $d_{\text{bv}} + L_{\text{o}}$ is the sum of the basic value and the staff movement factor, it should always be higher than 3 m. [m]
- d_{pp} is the phase-to-phase clearance distance. [m]

Once the distance between conductors has been established, the busbar/gateway span is derived from Equation 5.7.

$$L_{\text{sp}} = 2 \cdot d_{\text{bus}} + 2 \cdot d_{\text{bus-support}} \tag{5.7}$$

Where:

- L_{sp} is the busbar span. [m]
- d_{bus} is the distance between the conductors. [m]
- $d_{\text{bus-support}}$ is the distance between the conductor and the metallic support of the busbar. It equals L_{sp} but it never exceeds 7 m. [m]

Chapter 6

Substation Equipment

6.1 Power transformers

6.1.1 Two winding transformers

The power transformer is used to interconnect two networks of different voltage levels. In this case, the power transformer is designed to step up the voltage level from a generator operator to a distribution or transmission system operator.

The power transformer is by far the most important equipment installed in the step up substation. As the possibilities of selecting a power transformer are immense, a first scope is to determine its basic parameters such as power, short-circuit impedance, and voltage levels based on [16], [4] and [17] in obedience to the IEC standard and based on [18] and [19] according to the IEEE standard. A detailed study that would take into account the noise produced by the transformer, its cooling system, its insulation system or the tap changers is out of the scope. As a summary:

- The rated power of the transformer is equal to the power of the transformer bay.
- The short-circuit impedance is defined in Table 6.1 and Table 6.2 according to the IEC and IEEE standards respectively.
- The high voltage and medium voltage are chosen by the user.
- An oil-filled power transformer is considered.
- According to [15], the vector group for the step up transformer is Yd11.
- The primary winding will be solidly grounded. The secondary winding will be connected to earth with an earthing resistance and a reactance.

Table 6.1: Recognized minimum values of short-circuit impedance for transformers with two separate windings according to IEC. [4]

Rated power [MVA]	Short-circuit impedance [%]
<0.63	4
0.63 - 1.25	5
1.25 - 2.50	6
2.50 - 6.30	7
6.30 - 25	8
25 - 40	10
40 - 63	11
> 63	12.5

Table 6.2: Recognized minimum values of short-circuit impedance for transformers with two separate windings based on the BIL according to IEEE. [18]

High voltage BIL [kV]	Short-circuit impedance [%]
150	7
200	7.5
250	8
350	8.5
550	9.5
650	10
750	10.5

6.1.2 Three winding transformers

The power transformer with three-windings is mostly used to evacuate large amounts of capacity from medium to big plants. It is mostly used with the objective to reduce the cost of the transformers in the substation; hence, the final cost of the project.

Besides supplying the load, a tertiary winding can also serve:

- To stabilize voltages to the neutral when delta connected.
- To reduce the magnitude of third harmonics when delta connected.
- To control the value of the zero-sequence impedance.

For the impedance calculation of the three-winding power transformer, the total capacity connected to the secondary winding is considered. The impedances of the secondary windings are calculated based on that of the primary winding. The impedance percentage is the same for all the parallel transformers.

The capacity is assigned in an equal way between the two secondary windings. Hence, the number of the MV lines connected to both windings is similar in most cases.

The secondary short circuit current is calculated the same way as in the two-winding transformer, and it is considered for both secondary and tertiary windings.

6.2 Grounding equipment

The three-phase transformers, whose secondary winding are connected in star, have a neutral point that can be connected to the ground. However, the secondary winding of the power transformer chosen (Yd11) is connected in delta and there is no neutral point. In order to ground a delta winding, it is necessary to install an earthing transformer.

The main objective of an earthing device is to limit the earth fault currents. Furthermore, zig-zag transformers are one of the most commonly models used to ground a delta secondary winding of a transformer. Again, the neutral point of the zig-zag transformer can be connected to the ground by using a resistance. Hence, to calculate the reactance per phase of the zig-zag transformer as well as its resistance that will later connect its neutral point to the ground, the following steps have been followed.

According to [20], the parameter for rating the zig-zag transformer must be the thermal current. This is the current that flows through the neutral grounding reactor during a worst-case ground-fault scenario and it has been defined as the short-circuit current of the system.

To obtain the rated continuous current that can flow through the zig-zag transformer, [20] recommends to multiply the short-circuit current per the values that are presented in Table 6.3.

Table 6.3: Continuous current in percent of thermal current rating [%]. [20]

Rated time	Continuous current in percent of thermal current rating [%]
10s	3
1 min	7
> 10 min	30

In addition, there are standard values for continuous currents of grounding devices such as 100, 300, 500, 800, 1000 or 2000 A. Moreover, the duration of the fault considered is 10 seconds; hence, a 3% is applied to get the continuous current using Equation 6.1. After calculating $I_{\text{zig-zag}}$, the closest major standard value is chosen.

$$I_{\text{zig-zag}} = 0.03 \cdot I_{\text{sc}} \tag{6.1}$$

Where:

- $I_{\text{zig-zag}}$ is the rated continuous current that can flow through the zig-zag transformer. [A]
- I_{sc} is the short-circuit current. [A]

The phase reactance of the transformer is obtained using Equation 6.2.

$$X_{\text{g}} = \frac{X_0/X_1 \cdot U_{\text{mv}}}{\sqrt{3} \cdot I_{\text{sc}}} \tag{6.2}$$

Where:

- X_{g} is the earthing reactance. [Ω]

- X_0/X_1 is set to 10 in order to limit the overvoltages. [21]
- U_{mv} is the medium voltage level. [V]
- I_{sc} is the short-circuit current of the system. [A]

The earthing resistance is obtained using Equation 6.3.

$$R_g = \frac{U_{mv}}{\sqrt{3} \cdot I_{zig\text{-}zag}} \tag{6.3}$$

Where:

- R_g is the earthing resistance. [Ω]
- $U_{mv}/\sqrt{3}$ is the phase-to-earth medium voltage. [V]
- $I_{zig\text{-}zag}$ is the rated continuous current that flows through the zig-zag transformer. [A]

6.3 Surge arresters

A surge arrester is a protective device that limits overvoltages in order to protect electrical equipment. In general, surge arresters are located as close as possible to the equipment they may protect, which means at the termination of the overhead line and at the terminals of the transformers.

The protective level of a surge arrester has to be determined to withstand lightning overvoltages or high voltages due to switching events. However, during normal operation, they do not have effect on the electrical system. The surge arrester chosen is a metal oxide surge arrester.

The appropriate arrester has to be designed based on a detailed analysis of the protective characteristics required. In order to size the arrester in accordance to the IEC and the IEEE standards, [14], [22], [23] and [24] have been studied. Some of the most important parameters that must be calculated are the following ones:

- The rated voltage is the maximum permissible value at which the terminals of a surge arrester are designed to operate correctly under temporary overvoltages conditions.
- The continuous operation voltage is, usually, the maximum system line-to-ground voltage for metal oxide surge arresters.
- The capability of the surge arrester to withstand temporary overvoltages. These are power frequency overvoltages of long duration.
- The nominal discharge current that is the current that flows through the arrester due to a surge.
- The lightning and switching impulse protection levels for different nominal discharge currents.

6.3.1 Selection of the surge arrester

The procedure to calculate the lightning arrester according to [14] and [24] is next presented. To determine the continuous operating voltage of the lightning arrester, Equation 6.4 is used.

$$U_{cov} \geq \frac{f_{cov} \cdot U_m}{\sqrt{3}} \tag{6.4}$$

Where:

- U_{cov} is the continuous operating voltage. [V]
- U_m is the highest voltage for equipment. [V]
- f_{cov} is a factor that depends on the highest voltage for equipment where $f_{cov} = 1.05$ for $U_m \leq 100$ kV and $f_{cov} = 1.1$ for $U_m > 100$ kV.

The next step is to get the temporary overvoltage for the lightning arrester using Equation 6.5. The temporary overvoltages are produced by earth faults and load rejection. For this purpose, a TOV factor that takes into account the different overvoltages' origin will be estimated; and to do so, the system will be considered as solidly grounded. [22]

$$U_{tov} \geq f_{tov} \cdot U_{cov} \tag{6.5}$$

Where:

- U_{tov} is the temporary overvoltage for the lightning arrester. [V]
- U_{cov} is the continuous operating voltage. [V]
- f_{tov} is a factor that depends on the origin of the temporary overvoltages. As the system is solidly grounded, $f_{tov} = 1.4$.

The capability to withstand temporary overvoltages is given based on the equivalent 10 seconds duration overvoltage, which is calculated using the equation Equation 6.6.

$$U_{10s} = U_{tov} \cdot \left(\frac{\tau}{10}\right)^{\eta} \tag{6.6}$$

Where:

- U_{10s} is the equivalent 10 seconds duration overvoltage. [V]
- U_{tov} is the temporary overvoltage for the lightning arrester. [V]
- τ is the duration of the temporary overvoltage. A $\tau = 1$ has been considered.
- η is a coefficient. A $\eta = 0.02$ has been considered.

The rated voltage of the lightning arrester will be taken as the maximum between the equivalent 10 seconds duration overvoltage and the continuous operating voltage multiplied by a factor of 1.25, as shown in Equation 6.7.

$$U_r = max\,(1.25 \cdot U_{cov}\,,\ U_{10s}) \tag{6.7}$$

Where:

- U_{10s} is the equivalent 10 seconds duration overvoltage. [V]

- U_{cov} is the continuous operating voltage. [V]

The nominal discharge current will be $I_{nom} = 10$ kA for $U_m \leq 360$ kV and $I_{nom} = 20$ kA for $U_m > 360$ kV, according to [14].

To complete the process of calculating the lightning arrester, a database of commercial lightning arresters has been added to the software: [22], [25] and [26].

6.4 Circuit breakers

The circuit breaker is the element that closes and interrupts an electric circuit under load and fault conditions. The characteristics of a circuit breaker will identify its application in an electric system and its performance capabilities. To design a power circuit breaker, the main characteristics are defined according to [27], [28] and [29] for the IEC standard and to [30] for the IEEE standard.

The type of the circuit breaker affects the layout and configuration of the substation. Circuit breakers are usually classified as dead tank when their terminals are grounded or live tank when the interrupting mechanisms are mounted on an insulating porcelain column at line potential.

The rated voltage of the circuit breaker is the maximum voltage for which the breaker is designed. It is given by Equation 6.8.

$$U_{cb} = U_m \tag{6.8}$$

Where:

- U_{cb} is the rated voltage of the circuit breaker. [V]
- U_m is the highest voltage for the equipment. [V]

The rated normal current is the current that the circuit breaker can carry permanently under normal conditions of service. It is calculated by Equation 6.9. After obtaining the current, a R10 series standard current will be selected. [31]

$$I_{cb} = \frac{f_s \cdot P}{U \cdot \sqrt{3}} \tag{6.9}$$

Where:

- I_{cb} is the rated normal current of the circuit breaker. [A]
- f_s is a safety factor that equals 1.25.
- P is the power. [W]
- U is the line voltage. [V]

The rated short-circuit breaking current is the highest current that the circuit-breaker is able to break under certain conditions of behaviour prescribed in international standards. It is calculated by Equation 6.10.

$$I_{\text{sc-cb}} = I_{\text{sc}} \tag{6.10}$$

Where:

- $I_{\text{sc-cb}}$ is the rated short-circuit breaking current of the circuit breaker. [A]
- I_{sc} is the design short-circuit current. [A]

The rated frequency of the system that will be considered for calculating the rated short-circuit making current. The rated short-circuit making current is equal to the rated short-circuit breaking current multiplied by a factor, given in Equation 6.11.

$$I_{\text{msc-cb}} = f_{\text{msc}} \cdot I_{\text{sc-cb}} \tag{6.11}$$

Where:

- $I_{\text{msc-cb}}$ is the rated short-circuit making current of the circuit breaker. [A]
- f_{msc} is a factor equals to 2.5 if the frequency is 50 Hz and 2.6 if frequency is 60 Hz.
- $I_{\text{sc-cb}}$ is the rated short-circuit breaking current of the circuit breaker. [A]

6.5 Disconnectors

A disconnector is an off-load device without the capacity to break the electric circuit. There is a significant variety of disconnectors for use in outdoor substations. The selection of a disconnector will depend on the physical layout and on the space restrictions.

Disconnectors can be classified as single or double break with horizontal or vertical isolation. The most common type of double break disconnectors and the one chosen for pvDesign is the rotating center post.

To design a disconnector, the main characteristics are defined according to [27] and [32] for the IEC standard and to [30] for the IEEE standard.

The rated voltage is the maximum voltage for which the disconnector is designed. It is given by Equation 6.12.

$$U_{\text{d}} = U_{\text{m}} \tag{6.12}$$

Where:

- U_{d} is the rated voltage of the disconnector. [V]
- U_{m} is the highest voltage for the equipment. [V]

The rated normal current is the current that the disconnector can carry permanently under normal conditions of service. It is calculated by Equation 6.13. After obtaining the current, a R10 series standard current will be selected [31].

$$I_d = \frac{f_s \cdot P}{U \cdot \sqrt{3}} \quad (6.13)$$

Where:

- I_d is the rated normal current of the disconnector. [A]
- f_s is a safety factor that equals 1.25.
- P is the power. [W]
- U is the line voltage. [V]

The rated short-time withstand current is the current that the disconnector will be required to carry for one cycle. It is calculated by Equation 6.14.

$$I_{sc\text{-}d} = I_{sc} \quad (6.14)$$

Where:

- $I_{sc\text{-}d}$ is the rated short-time withstand current of the disconnector. [A]
- I_{sc} is the design short-circuit current. [A]

The rated peak withstand current that is equal to the rated short-time withstand current multiplied by a factor, given in Equation 6.15.

$$I_{psc\text{-}d} = f_{psc} \cdot I_{sc\text{-}cb} \quad (6.15)$$

Where:

- $I_{msc\text{-}cb}$ is the rated short-circuit making current of the disconnector. [A]
- f_{psc} is a factor equals to 2.5 if the frequency is 50 Hz and 2.6 if frequency is 60 Hz.
- $I_{sc\text{-}cb}$ is the rated short-circuit breaking current of the disconnector. [A]

6.6 Current transformers

A current transformer is an instrument transformer intended to measure the current. The primary winding of the current transformer is connected in series with the conductor that is carrying the current that has to be controlled.

The main functions of these devices are to transform the current of high voltage systems to a value that a relay can measure and to insulate the metering circuit from high voltage systems.

The ideal location of a current transformer within the substation is generally as close as possible to the equipment to be protected and measured. For dead tank circuit breakers, the secondary winding of the instrument transformer is mounted over the same structure. For live tank circuit breakers, the current transformer is usually installed in a separate mounting structure.

The current transformers can be grouped into two categories: metering service and relay service. On one hand the current transformers designed for metering services are not prepared for protecting services. On the other hand, current transformers used for relay services should not be used for high-accuracy metering applications.

To design a current transformer, the main characteristics are defined according to [33] and [34] conforming to the IEC standard and according to [35] and [36] for the IEEE standard. In the latter, the calculations and standard values are applicable only at 60 Hz.

The rated voltage is the maximum voltage for which the current transformer is designed. It is given by Equation 6.16.

$$U_{ct} = U_m \tag{6.16}$$

Where:

- U_{ct} is the rated voltage of the current transformer. [V]
- U_m is the highest voltage for the equipment. [V]

The rated primary current that the current transformer has to withstand in continuous operation is calculated by Equation 6.17. After obtaining the current, the closest standard current will be selected depending on the chosen standard. [34] [35]. In this case, The R10 values are not followed.

$$I_{ct} = \frac{f_s \cdot P}{U \cdot \sqrt{3}} \tag{6.17}$$

Where:

- I_{ct} is the rated normal current of the current transformer. [A]
- f_s is a safety factor that equals 1.25.
- P is the power. [W]
- U is the line voltage. [V]

According to the IEC standard, the rated secondary current can be 1 A or 5 A. When instruments or relays are close to the protected or measured device, the secondary selected current is 5A. However, 1 A is preferably selected when the distance between the device and the instrument transformer is above 10 m. As control units are not calculated at the moment, 5 A is chosen. As for the IEEE standard, the rated secondary current is always 5 A.

The rated continuous thermal current is the current that flows in the primary winding with temperature rise exceeding standard requirements. In general it is equal to the primary current. It is given by Equation 6.18.

$$I_t = I_{ct} \tag{6.18}$$

Where:

- I_t is the rated continuous thermal current of the current transformer. [A]

- I_{ct} is the rated normal current of the current transformer. [A]

The rated short-time thermal current is the maximum current that it can withstand for a period of one second without breaking the insulator. If it is not specified, it can be equal to the system's short-circuit current. It is given by Equation 6.19.

$$I_{sc\text{-}ct} = I_{sc} \tag{6.19}$$

Where:

- $I_{sc\text{-}ct}$ is the rated short-time thermal current. [A]
- I_{sc} is the design short-circuit current. [A]

The first peak of current during a short-circuit event is the dynamic current. It can reach 2.5 times the rated short-time thermal current in obedience to the international standard and 2.7 times the same rated current according to the IEEE standard . It is given in Equation 6.20.

$$I_{dyn} = f_{dyn} \cdot I_{sc\text{-}ct} \tag{6.20}$$

Where:

- I_{dyn} is the dynamic current. [A]
- f_{dyn} is a factor equals to 2.5 or 2.7 depending on the standard followed.
- $I_{sc\text{-}ct}$ is the rated short-time thermal current. [A]

On one hand, the IEC standard [34] is used for defining the burdens and accuracies. The possible burdens are 2.5, 5, 10, 15, 30 VA. The metering accuracies are 0.2, 0.2s, 0.5 and 0.5s and the protection accuracies are 5P and 10P. Burdens for protection services will be higher than those used for metering services.

On the other hand, the IEEE standard [35] is used for defining the burdens, designations, and accuracies. The possible burdens are 2.5, 5, 12.5, 22.5, 45 VA. The corresponding assignations are B-0.1, B-0.2, B-0.5, B-0.9, B-1.8. The metering accuracies are 0.15s, 0.15, 0.15N, 0.3s, 0.3, 0.6, and 1.2 and the protection accuracies are C100, C200, C300, C400, C500, C600, C700, C800. Burdens for protection services will be higher than those used for metering services.

6.7 Voltage transformers

A voltage transformer is an instrument transformer intended to measure the primary voltage. The primary winding of the voltage transformer is connected in shunt with a power supply circuit. The voltage transformers can be connected to the buses and usually as close as possible to the termination of the overhead lines.

Voltage transformers can be of capacitive or inductive types. An inductive voltage transformer is selected for distribution grids. The main characteristics of a voltage transformer are defined according to both the IEC standard in [33], [37] and [38] and to the IEEE standard in [35] and [39].

The primary voltage is the voltage of the system, given in Equation 6.21

$$U_{\text{vt}} = \frac{U}{\sqrt{3}} \tag{6.21}$$

Where:

- U_{vt} is the primary voltage of the voltage transformer. [V]
- U is the line voltage. [V]

According to the IEC standard [37], the secondary rated current of the equipment can be 100 or 110 V. Differently, the IEEE standard states that the secondary rated current can be 115 when the voltage is above 25 kV and 120 V when it is up to 25 kV [35]. Regarding both high and low voltage, the single-phase line to ground voltage will be taken, that is, the voltage divided by $\sqrt{3}$ in case of a star connection and by 3 for delta windings.

The standards [37] and [38] have been followed to define the burdens and accuracies for the international standard and [35] has been followed to define the burdens, assignations, and accuracy classes according to the IEEE standard.

As reported by the IEC, the burdens are 1, 2.5, 5, 10, 25 50, 100 VA. The accuracy classes are 0.1, 0.2, 0.5, 1, 3 for metering purposes;3P and 6P for protection services; and 0.5-3P for metering/protection services.

With regard to the IEEE standard, the burdens are 12.5, 25, 35, 75, 200, 400 VA and their corresponding designations are W, WX, WXM, WXMY, WXMYZ, WXMYZZ. In addition, the accuracy classes are 0.15, 0.3, 0.6, and 1.2 for metering purposes and 1.2 for protection purposes.

For both standards, these cores follow the same principles applied for current transformers: burdens for protection services will be higher than those used for metering services.

6.8 Cables

The cables that connect the primary medium voltage cubicles with the power transformers are calculated based on the IEC [40] or NEC [41] standards. The cables will be sized following three criteria:

- The maximum current-carrying capacity. The maximum 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 voltage drop.
- The 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.

The most significant criterion that affects the high power cables is the maximum current-carrying capacity. For more details about how to size the cables, it is recommended to read the electrical methodology which is available in pvDesign. In this document, only the most important parameters to size the cables are mentioned:

- Type of installation: The cables are directly buried.
- System: AC three-phase medium voltage system.
- Number of cores: Single.
- Conductor material: Aluminium.
- Insulation: XLPE.
- Soil temperature: 25°C. To define the soil temperature correction factor.
- Soil resistivity: 1 K·m/W. To compute the soil resistivity correction factor.
- Cables' laying depth: 0.9 m. This is an input to obtain the depth of burial correction factor.
- Maximum number of circuits per trench: 1. This will be taken into account to calculate the cable grouping correction factor.
- Maximum number of three-phase conductor per system: Up to 6. This will be taken into account to calculate the cable grouping correction factor.

The length of the cable is calculated based on the following assumptions:

- For the switching and breaking station, the length considered is 50 m.
- For the substation the length of the cables is computed according to the safety distances the bay width and the road width.

6.9 Capacitor Banks

A capacitor bank is a group of capacitors connected in series or in parallel. These electrical components are used to compensate the reactive energy generated by the inductive loads in the plant, improving the power factor and voltage stability.

When designing a PV plant, the utility company or the grid operator will define a required power factor at a given point of the facility. There are two main strategies to compensate the inductive power factor in photovoltaic plants: installing additional inverters or adding capacitor banks. The decision of the required strategy is highly dependant on the cost of the equipment, which will not be covered in this methodology.

The capacitor banks will be placed at the medium voltage switch-gears of the power transformers within the step up substations. The medium voltage side is selected to reduce the cost of the equipment and the switching stress.

6.9.1 Reactive Capacity

When the capacitor bank strategy is applied, a study of the reactive power must be carried out in order to reach the desired power factor at the given point of measurement.

The calculation of this reactive power is not in the scope of this methodology, but a brief summary will be presented:

The electrical circuit used is based on the power flow model [42], which represents an equivalent circuit of all the elements in the PV plant, substation and transmission line.

The transformers are modelled as a T two-port network (see Figure 6.1), where the parallel branch represents the magnetization losses and the series impedances represent the short circuit impedance.

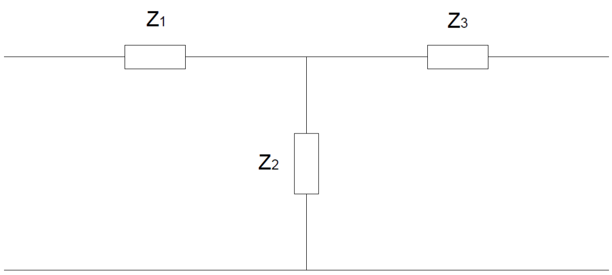

Figure 6.1: Electrical schema of a T two-port network. Source: Own elaboration.

The transmission lines and mv lines are modelled as PI two-port network, with parallel capacitance, as shown in Figure 6.2.

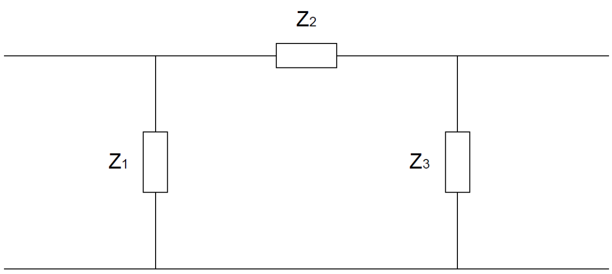

Figure 6.2: Electrical schema of a PI two-port network. Source: Own elaboration.

The calculations performed are based on the load flow calculations using the Newton-Raphson method, resulting in a value of active and reactive power at each node of the system. Using this information, the capacitor banks are sized to compensate for the inductive power introduced by the different elements in the plant.

6.9.2 Capacitor Bank Requirements

In a PV plant, there is a set of elements that can produce inductive losses, specifically the transformers and cables. The first step when sizing a capacitor bank is to calculate the inductive load that will be compensated with the capacitor bank.

The inductive losses incurred by each system will be obtained from the difference in reactive capacity at the input and output of each system individually.

Since the capacitor banks are placed in the medium voltage switch-gears of the substation, they will be able to compensate for the reactive power of upstream systems (mv lines, power stations and lv lines) and downstream systems (power transformer and transmission line).

Determining the reactive power to compensate from upstream equipment is straight forward. The reactive capacity to compensate will be the sum of the inductive losses of all the upstream systems connected to the switch-gear.

However, the compensation of the downstream systems is not that simple, as the reactive compensation will have to be distributed across different capacitor banks. The reactive compensation required will be distributed across the capacitor banks depending on the mv switch-gears capacity. This means that the capacitor banks connected to bigger switch-gears will compensate for more reactive power than the ones connected to smaller switch-gears.

6.9.3 Capacitor Bank Feeder

The previous section presented the reactive compensation requirements that each capacitor system must fulfil to compensate for the inductive losses of the different systems.

In this section, the actual sizing of the different elements in the capacitor bank feeder will be presented. The electrical components included in the capacitor feeder are the following:

- One disconnector, sized according to Section 6.5 using the current of the switch-gears' line with more power.
- One circuit breaker, sized according to Section 6.4 using the current of the switch-gears' line with more power.
- One current transformer, sized according to Section 6.6 using the total reactive power of the capacitor feeder.
- One voltage detector.
- One detuned reactor to reduce the effect of harmonics, as well as to reduce the switch current of the feeder. The sizing of this component will be covered later in this section.
- One grounding disconnector, sized according to Section 6.5 using the current of the switch-gears' line with more power. This component will be connected to the output of the capacitor bank.
- One capacitor bank connected in star configuration. The sizing of this component will be covered later in this section.

For switching and breaking stations, the current transformer, circuit breaker and grounding disconnector are removed and replaced with a fuse after the first disconnector.

An example of a capacitor bank feeder electrical representation is shown in 6.3.

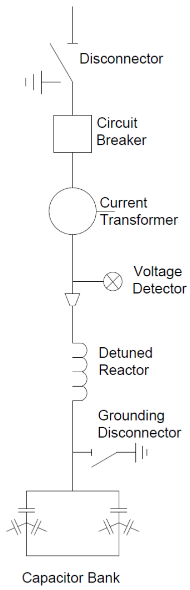

Figure 6.3: An example of a capacitor feeder for a 20 kV switchgear. Source: Simulation using pvDesign.

6.9.4 Detuned reactor and capacitor bank sizing

When operating a capacitor bank in a substation, the appearance of harmonics can become problematic, as it causes overheating and can potentially result in resonance effects, which can ultimately cause damage to the different components. To fix this issue, a detuned reactor is connected in series with the capacitor bank. However, this reactor will reduce the reactive compensation of the capacitor bank, as it will include additional inductive losses, meaning that the capacitors will need to be oversized to compensate for this effect.

The first step towards the sizing of the detuned reactor is the selection of the detuned factor. This value defines a relationship between the reactor's impedance and the capacitor's impedance. Typical values for the detuned factor are 5.67%, 7% and 14%. These values are also related to the resonance frequency filtered, which is shown in Table 6.4

Table 6.4: Typical detuned factors and resonance frequencies filtered

Detuned Factor [%]	Fr/Fn	Fr (50Hz) [Hz]	Fr (60Hz) [Hz]
5.67	4.2	210	252
7	3.78	189	227
14	2.68	134	160

According to IEEE 1531-2020 [43], "where power factor correction is most important, systems tuned to the 4.2nd harmonic or below can generally be safely applied in this manner". In this regard, a 5.67% of detuned factor could be an option, as it would reduce the size of the capacitor bank because of having a smaller reactor. However, a detuned factor of 7% will be used to size the capacitor bank to improve the harmonic filtering and the system stability.

Once the detuned factor has been defined, the capacitor bank can be sized. The first step is to calculate the total reactance of the capacitor feeder, which will be equal to the sum of the complex reactances of the capacitor and the reactor. The total reactance will be calculated according to Equation 6.22:

$$X_T = \frac{U^2}{Q_{req}} \tag{6.22}$$

Where:

- X_T is the total reactance of the capacitor feeder. [Ω]
- U is the medium voltage. [V]
- Q_{req} is the required reactive compensation. [MVAr]

The reactance of the capacitor can then be obtained from Equation 6.23.

$$X_C = \frac{X_T}{1 - (D_f/100)} \tag{6.23}$$

Where:

- X_C is the reactance of the capacitor. [Ω]
- X_T is the total reactance of the capacitor feeder. [Ω]
- D_f is the detuned factor, equal to 7% , obtained from Table 6.4. [%]

The detuned reactor's reactance can then be calculated using Equation 6.24.

$$X_L = X_C \cdot (D_f/100) \tag{6.24}$$

Where:

- X_L is the reactance of the detuned reactor. [Ω]
- X_C is the reactance of the capacitor. [Ω]
- D_f is the detuned factor, equal to 7% , obtained from Table 6.4. [%]

The current flowing through the feeder will be calculated from Equation 6.25.

$$I_{cap} = \frac{Q_{req}}{\sqrt{3} \cdot U} \tag{6.25}$$

Where:

- I_{cap} is the current through the capacitor feeder. [A]
- Q_{req} is the required reactive compensation. [MVAr]
- U is the medium voltage. [V]

From Equation 6.24 and Equation 6.25, the voltage across the inductor can be calculated using Equation 6.26.

$$U_L = \sqrt{3} \cdot I_{cap} \cdot X_L \tag{6.26}$$

Where:

- U_L is the voltage across the detuned reactor. [V]
- I_{cap} is the current through the capacitor feeder. [A]
- X_L is the reactance of the detuned reactor. [Ω]

In order to calculate the voltage at the capacitor bank point, Equation 6.27 will be used.

$$U_C = cU + U_L \tag{6.27}$$

Where:

- U_C is the voltage at the capacitor input. [V]
- c is the over-voltage factor of 1.1. For normal conditions, an over-voltage factor of 1.0 will be considered.
- U is the medium voltage. [V]
- U_L is the voltage across the detuned reactor. [V]

The required reactive capacity that the capacitor bank and detuned reactor will provide and consume respectively are presented in Equation 6.28 and Equation 6.29

$$Q_C = \frac{U_C^2}{X_C} \tag{6.28}$$

$$Q_L = \frac{U_L^2}{X_L} \tag{6.29}$$

Where:

- Q_C is the reactive capacity of the capacitor (capacitive or leading). [MVAr]
- U_C is the voltage at the capacitor input. [V]
- X_C is the reactance of the capacitor. [Ω]
- Q_L is the reactive capacity of the detuned reactor (inductive or lagging). [MVAr]
- U_L is the voltage across the detuned reactor. [V]
- X_L is the reactance of the detuned reactor. [Ω]

Chapter 7

Design of the bus in air insulated substations

This chapter describes the process for designing the busbar of an air-insulated substation based on main standards such as IEC and IEEE as well as practical guides such as Cigré technical brochures. Therefore, the objective is to obtain the dimensions of a rigid bus, the forces acting on the bus structure, and the information related to the busbar's technical properties: corona effect, thermal short-circuit effects, among others. This chapter will provide the necessary information to calculate the dimensions of a rigid bus.

7.1 Introduction

The following example clarifies the process of designing a rigid busbar for an air-insulated substation using the information presented in [44] and [45]. The parameters required for the bus design are:

- The installed capacity of the photovoltaic plant, P_{ac} in [W].
- The high voltage level U_{hg} in [V].
- The number of transformer bays, calculated in Section 2.1, n_{Tr}.
- The span of the rigid bus, calculated in Subsection 5.2.5, L_{sp} in [m].
- The distance between conductors, calculated in Subsection 5.2.5, d_{bus} in [m].
- The height of the bus, calculated in Subsection 5.2.3, h_{busbar} in [m].
- The rated lightning impulse withstand voltage, calculated in Section 4.7, U_{liwv} in [V].
- The design short-circuit current given in Section 3.1, I_{sc} in [A].
- The frequency of the system, f in [Hz].
- The ambient temperature, T_{amb} in [°C].
- The elevation above the sea, H in [m].

With the parameters listed above, the rigid bus' dimensions are obtained. In addition, the following design parameters are determined:

- The bus conductor size that withstands both the load current and the short circuit current.

- The maximum allowable bus length based on vertical deflection.
- The forces that are applied on the substation buses based on weight, ice, short circuit, and wind loads.
- The maximum corona on the bus.
- The thermal expansion's requirements.
- The required insulator that withstands bus loads.

7.2 Specific properties of the buses

The available buses for the study are summarized in Table 7.1. The buses are obtained from [46] and the values are recommended from transmission system operators such as Red Eléctrica Española. Other than the external and internal diameter, the thickness, and the ampacity that the pipes withstand, there are other important properties that play a significant role in the process.

Table 7.1: Technical characteristics of 6063 T6 aluminium tubes for substations. [46]

External diameter d_{ext} [m]	Internal diameter d_{int} [m]	Thickness t [m]	Ampacity A_{bus} [A]
0.063	0.047	0.008	1546
0.100	0.084	0.008	2270
0.120	0.104	0.008	2657
0.150	0.134	0.008	4838
0.150	0.125	0.008	2976
0.200	0.190	0.005	4589
0.200	0.188	0.006	3575
0.200	0.184	0.008	4154
0.200	0.180	0.010	4589
0.200	0.176	0.012	5024
0.250	0.240	0.005	5507
0.250	0.238	0.006	6086
0.250	0.234	0.008	6956
0.250	0.230	0.010	7729
0.250	0.226	0.012	8502

The section of the bus is obtained from Equation 7.1.

$$A_c = \pi \cdot \frac{d_{ext}^2 - d_{int}^2}{4} \tag{7.1}$$

Where:

- A_c is the section of the bus. [m^2]
- d_{ext} is the external diameter of the bus. [m]
- d_{int} is the internal diameter of the bus. [m]

The moment of resistance of the pipe is calculated using Equation 7.2

$$S_c = \pi \cdot \frac{d_{ext}^4 - d_{int}^4}{32 \cdot d_{ext}} \quad (7.2)$$

Where:

- S_c is the moment of resistance of the bus. [m^3]
- d_{ext} is the external diameter of the bus. [m]
- d_{int} is the internal diameter of the bus. [m]

The moment of inertia is obtained using Equation 7.3

$$I = \pi \cdot \frac{d_{ext}^4 - d_{int}^4}{64} \quad (7.3)$$

Where:

- I is the bending moment of inertia. [m^4]
- d_{ext} is the external diameter of the bus. [m]
- d_{int} is the internal diameter of the bus. [m]

The unitary weight of the pipe is represented by Equation 7.4

$$u_{bus} = w_{Al} \cdot A_c \quad (7.4)$$

Where:

- u_{bus} is the bus unitary weight. [kg/m]
- w_{Al} is the specific weight for aluminium that is equal to 2700. [kg/m^3]
- A_c is the section of the bus. [m^2]

Other significant technical properties are:

- E is the modulus of elasticity for aluminium, which is equal to $7 \cdot 10^{10}$ [N/m^2].
- F_u is the ultimate tensile strength for aluminium that is equal to $220 \cdot 10^6$ [N/m^2].
- F_y is the tensile yield strength for aluminium that is equal to $185 \cdot 10^6$ [N/m^2].
- α_c is the coefficient temperature expansion, which is equal to 0.023 [mm/m°C].

7.3 Minimum size for load current

The load current carried by the bus is calculated using Equation 7.5.

$$I_{load} = \frac{f_{growth} \cdot P_{ac}}{U_{hg} \cdot \sqrt{3}} \quad (7.5)$$

Where:

- I_{load} is the load current that the bus will carry. [A]
- f_{growth} is a factor that equals 1.25.
- P_{ac} is the installed capacity of the photovoltaic plant. [W]
- U_{hg} is the high voltage level. [V]

For an acceptable design, the condition given in Equation 7.6 has to be fulfilled.

$$\boxed{I_{\text{load}} \leq A_{\text{bus}}} \tag{7.6}$$

Where:

- I_{load} is the load current that the bus will carry. [A]
- A_{bus} is the ampacity given in Table 7.1. [A]

7.4 Minimum size for short-circuit current

The bus conductor should be able to withstand a short-circuit current [44], given by Equation 7.7 for a short period of time.

$$I_{\text{bus sc}} = C \cdot 10^{12} \cdot A_{\text{c}} \sqrt{\frac{1}{t} \cdot \log_{10}\left(\frac{T_{\text{f}} - 20 + 15150/G}{T_{\text{i}} - 20 + 15150/G}\right)} \tag{7.7}$$

Where:

- $I_{\text{sc bus}}$ is the short-circuit current that the bus is able to withstand. [A]
- C is a constant that is equal to 2.232 $\cdot 10^6$.
- t is the assigned short-circuit time given in Section 3.4, which is equal to 1. [s]
- A_{c} is the conductor area. [m^2]
- G is the conductivity for aluminium that is equal to 53%.
- T_{f} is the maximum conductor temperature and it is equal to 250. [°C]
- T_{i} is the initial conductor temperature and it is equal to 90. [°C]

For an acceptable operation, the condition given in Equation 7.8 has to be fulfilled.

$$\boxed{I_{\text{sc}} \leq I_{\text{bus sc}}} \tag{7.8}$$

Where:

- I_{sc} is the design short-circuit current given in Section 3.1. [A]
- $I_{\text{bus sc}}$ is the short-circuit current that the bus is able to withstand. [A]

7.5 Rigid bus loads

7.5.1 Calculation of the forces by unit length applied on the bus

The maximum force by unit length on the conductor should first be determined. Hence, the forces that should be considered are the total gravitational weight, the wind force, and the short circuit force. Some of the forces occur in the vertical direction whereas the other occurs in the horizontal direction. The forces may not happen at the same time; however, considering a worst case scenario, all the forces are combined and taken into account. Therefore, the worst case scenario leads to a smaller allowable spans for buses and higher loads for insulators.

The maximum force acting on the conductor is therefore, the modulus of the sum of the forces considered at the same time in both the vertical and horizontal direction.

Weight force by unit length

The weight force by unit length on the bus is given by Equation 7.9.

$$p_{\text{weight}} = \left(u_{\text{bus}} + u_{\text{damper}}\right) \cdot g = u_{\text{bus}} \cdot C_{\text{damper}} \cdot g \tag{7.9}$$

Where:

- p_{weight} is the weight force by unit length. [N/m]
- u_{bus} is the bus unitary weight. [kg/m]
- u_{damper} is the damper unitary weight. [kg/m]
- C_{damper} is a factor equals to 125%. The weight of the damper is taken as the 25% of the weight of the bus.
- g is the gravity of Earth. [m/s^2]

Ice force by unit length

The ice force by unit length on the bus is calculated based on [47].

- $p_{\text{ice}} = 0$ for $H < 500$ m.
- $p_{\text{ice}} = 1.8\sqrt{d_{\text{ext}}}$ for $500 < H < 1000$ m.
- $p_{\text{ice}} = 3.6\sqrt{d_{\text{ext}}}$ for $1000 < H < 2000$ m.

Where:

- p_{ice} is the ice force by unit length. [N/m]
- d_{ext} is the external diameter of the bus. [m]
- H is the elevation above the sea level. [m]

Short-circuit force by unit length

In order to compute the short-circuit force by unit length, the calculation model in [45] has been followed. First, the peak short-circuit current has been estimated by Section 3.3.

The maximum short circuit force by unit length on the buses is obtained according to Equation 7.10.

$$p_{m3} = \frac{\mu_0}{2\pi} \frac{\sqrt{3}}{2} \frac{1}{d_{bus}} I_{peak}^2 \tag{7.10}$$

Where:

- p_{m3} is the maximum short-circuit force by unit length. [N/m]
- μ_0 is the the vacuum permeability.
- d_{bus} is the distance between conductors, calculated in Subsection 5.2.5. [m]
- I_{peak} is the peak short circuit current. [A]

Wind force by unit length

The wind force by unit length on cylindrical surfaces is calculated using Equation 7.11.

$$p_{wind} = d_{ext} \cdot P_{air} \cdot \left(\frac{V_{wind}}{V_{ref}}\right)^2 \tag{7.11}$$

Where:

- p_{wind} is the wind force by unit length. [N/m]
- d_{ext} is the external diameter of the bus. [m]
- P_{air} is the air pressure, taken as 700 [N/m^2]
- V_{wind} is the wind speed. Here, the worst case scenario has been estimated in which the wind speed is 120 [km/h]
- V_{ref} is a reference wind speed that is equal to 120 [km/h]

7.5.2 Reactions

The loads on the buses are transmitted to the insulators. Therefore, the strength of the insulator has to be calculated. As the insulator is determined, the wind force on this element should be considered when combining all the forces.

This section presents a simplified method for analyzing the reactions of different loads from a static point of view. The forces to consider in the evaluation of the net reaction on an insulator consist of what it follows.

The force that the insulator withstands will result from the combination of the gravitational, wind, and short circuit loads on the bus. This force is obtained as a function of the effective conductor's span length supported by the insulator. In addition, the effective conductor's span length L_E depends on the span length and the bus-support conditions.

Moreover, the bus-support conditions depend on the number of transformer bays. Hence, the effective conductor span length L_E is obtained using Equation 7.12. For a single span (that is single bus bar configuration with one transformer), the coefficient is the maximum of the support conditions' values.

$$L_E = C_{reaction} \cdot L_{sp} \tag{7.12}$$

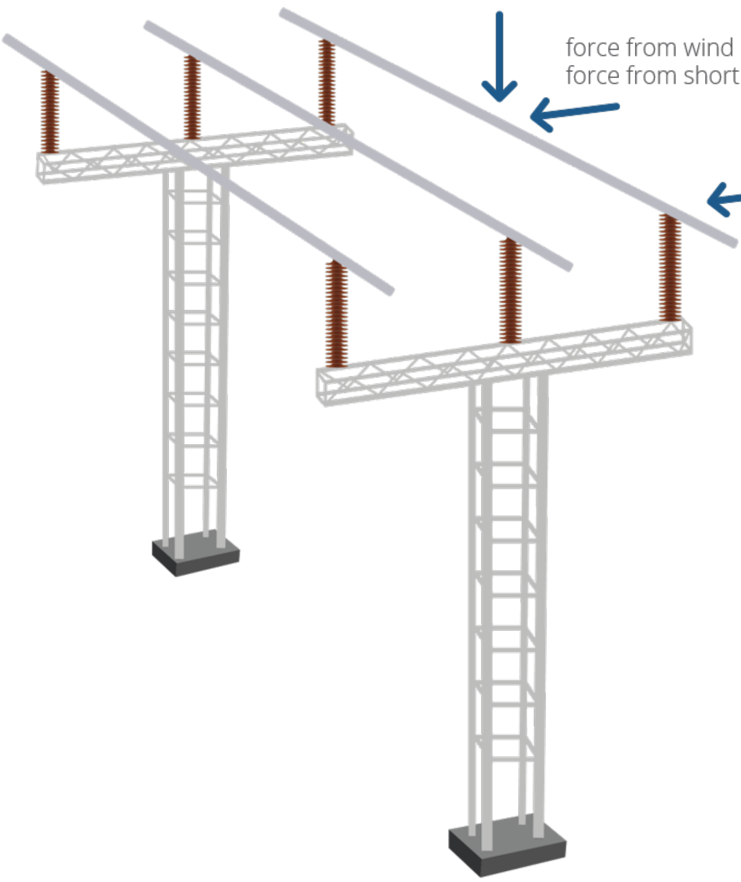

Figure 7.1: The forces that affect the structure of a busbar. Source: Own elaboration

Where:

- L_E is the effective conductor span length. [m]
- L_{sp} is the span of the rigid bus. [m]
- $C_{reaction}$ is the reaction coefficient given in Table 7.2.

Table 7.2: Maximum reaction coefficients for common bus arrangements. [44], [48]

Bus configuration	Support conditions					Reaction coefficient
	S1	S2	S3	S4	S5	
Single-span	P	P				0.5
	P	F				0.625
	F	F				0.5
Two continuous-span	P	C	P			1.25
Three continuous-span	P	C	C	P		1.1
Four continuous-span	P	C	C	C	P	1.145
More than 4						1.145
For insulator	P	F				0.625

The reactions on the supports due to the weight, ice, and wind loads by unit length are obtained using Equation 7.13

$$F = p \cdot L_e \tag{7.13}$$

Where:

- F is a force (gravitational: weight, ice, and wind on bus). [N]
- p is a force by unit length. [N/m]
- L_E is the effective conductor span length. [m]

The reactions on the supports caused by the short circuit current forces by unit length are obtained using Equation 7.14

$$F_{sc} = p_r \cdot L_e \tag{7.14}$$

Where:

- F_{sc} is the force on the supports. [N]
- p_r is the equivalent static short circuit force by unit length obtained from Equation 7.15. [N/m]
- L_E is the effective conductor span length. [m]

$$p_r = V_r \cdot V_F \cdot p_{m3} \tag{7.15}$$

Where:

- p_r is the equivalent static short circuit force by unit length. [N/m]
- p_{m3} is the maximum short circuit force by unit length. [N/m]
- V_r measures the relation of the different dynamic mechanical stresses on the bus due to three-phase tripping.
- V_F measures the ratio between dynamic and static forces on the supports.

The reactions on the bus supports caused by wind force on the insulators are obtained using Equation 7.16.

$$F_{\text{wind insulator}} = p_{\text{wind insulator}} \cdot L_{\text{e insulator}} = p_{\text{wind insulator}} \cdot C_{\text{reaction insulator}} \cdot L_{\text{insulator}} \tag{7.16}$$

Where:

- $F_{\text{wind insulator}}$ is the force due to the wind on the insulators. [N]
- $p_{\text{wind insulator}}$ is the force by unit length due to the wind on the insulators. [N/m]
- $C_{\text{reaction insulator}}$ is the reaction coefficient for insulator obtained from Table 7.2.
- $L_{\text{insulator}}$ is the insulator length. [m]

The total force on the bus supports is the results of the vector sum of all forces as shown in Equation 7.17

$$F_T = \sqrt{\left(F_{\text{weigth}} + F_{\text{ice}}\right)^2 + \left(F_{\text{sc}} + F_{\text{wind}} + F_{\text{wind insulator}}\right)^2} \tag{7.17}$$

7.5.3 Stresses on bus

A bus will be able to withstand the combination of all the forces if the condition given in Equation 7.18 is fulfilled. [45]

$$\boxed{\sigma_T \leq q \cdot F_y} \tag{7.18}$$

Where:

- σ_T is the total stress on the bus calculated from Equation 7.24. [N/m^2]
- q is a factor given by Equation 7.19.
- F_y is the tensile yield strength for aluminium that is equal to 185 $\cdot 10^6$ [N/m^2]

$$q = 1.7 \frac{1 - (1 - 2t/d_{\text{ext}})^3}{1 - (1 - 2t/d_{\text{ext}})^4} \tag{7.19}$$

Where:

- q is a factor for cylindrical tubes.
- t is the thickness of the bus. [m]
- d_{ext} is the external diameter of the bus. [m]

The stresses on the bus caused by gravitational and wind forces are obtained using Equation 7.20.

$$\sigma = \frac{p \cdot C_{\text{stress}} \cdot L_{\text{sp}}^2}{S_c} \tag{7.20}$$

Where:

- σ is the mechanical stress caused by gravitational or wind forces by unit length on the bus. [N/m^2]
- p is the gravitational or wind force by unit length. [N/m]
- C_{stress} is the moment coefficient given in Table 7.3.
- L_{sp} is the span of the rigid bus. [m]
- S_c is the moment of resistance of the bus. [m^3]

To obtain the mechanical stress on the bus caused by the short circuit load, the IEC standard [45] has been followed and Equation 7.21 has been used.

$$\sigma_{sc} = \frac{V_\sigma \cdot V_r \cdot \beta \cdot p_r \cdot L_{sp}^2}{8S_c} \tag{7.21}$$

Where:

- σ_{sc} is the mechanical stress caused by the short circuit force by unit length on the insulator. [N/m^2]
- V_σ measures the ratio between dynamic and static stresses on the supports.
- V_r measures the relation of the different dynamic mechanical loads on the bus due to three-phase tripping.
- β is a factor.
- p_r is is the equivalent static short-circuit force by unit length. [N/m]
- L_{sp} is the length of the bus. [m]
- $S_{insulator}$ is the moment of resistance of the bus. [m^3]

The stress on the bus caused by the wind force on the insulator is obtained using Equation 7.22.

$$\sigma_{wind\ insulator} = \frac{p_{wind} \cdot C_{stress\ insulator} \cdot L_{insulator}^2}{S_{insulator}} \tag{7.22}$$

Where:

- $\sigma_{wind\ insulator}$ is the mechanical stress caused by the wind force on the insulator. [N/m^2]
- p_{wind} is the wind force on the insulator by unit length. [N/m]
- $C_{stress\ insulator}$ is the moment coefficient given in Table 7.3.
- $L_{insulator}$ is the length of the insulator. [m]
- $S_{insulator}$ is the moment of resistance of the insulator. The moment of resistance of the insulator is obtained from Equation 7.23. [m^3]

$$S_{insulator} = \pi \frac{d_{ext\ insulator}}{32} \tag{7.23}$$

Where:

- $d_{ext\ insulator}$ is the external diameter of the insulator. [m]

The total force on the bus supports is the result of the vector sum of all the forces as shown in Equation 7.24

$$\sigma_T = \sqrt{(\sigma_{weigth} + \sigma_{ice})^2 + (\sigma_{sc} + \sigma_{wind} + \sigma_{wind\ insulator})^2} \tag{7.24}$$

Table 7.3: Maximum stress coefficients for common bus arrangements. [48]

Bus configuration	Support conditions					Moment coefficient
	S1	S2	S3	S4	S5	
Single-span	P	P				1/6
	P	F				1/8
	F	F				1/12
Two continuous-span	P	C	P			0.07
Three continuous-span	P	C	C	P		0.08
More than 3						0.08
For insulator	P	F				1/8

7.6 Allowable Span

The maximum length of the rigid bus may comply with two criteria. The first criterion provides a method to compute the allowable length based on the deflection limit. The other criterion will take into consideration the fibre stress [44]. The minimum value will be chosen to consider the worst-case scenario's result.

7.6.1 Allowable span based on deflection limit

The maximum length based on the deflection limit of the aluminium is calculated using the Equation 7.25.

$$L_v = \left(\frac{185 \cdot E \cdot I \cdot f_{def}}{p_g} \right)^{\frac{1}{3}} \quad (7.25)$$

Where:

- L_v is maximum length based on the deflection limit. [m]
- E is the modulus of elasticity for aluminium. [N/m^2]
- I is the bending moment of inertia. [m^4]
- f_{def} is the deflection limit.
- p_g is the gravitational force by unit length, the sum of the weight and ice loads $p_g = p_w + p_i$ in [N/m]

The deflection limit is obtained from [46]. If there is no information regarding the deflection limit in the data sheet previously commented, a default value of 0.67% will be taken.

7.6.2 Allowable span based on fibre stress

The allowable span based on the fibre stress considers the total forces that are applied on the bus and the ultimate tensile strength of the aluminium. It is obtained using the Equation 7.26.

$$L_s = \sqrt{\frac{16 \cdot I \cdot f_{weld} \cdot F_u}{p_T \cdot d_{ext}}} \quad (7.26)$$

Where:

- L_s is the maximum length based on the fibre stress. [m]
- I is the bending moment of inertia. [m^4]
- f_{weld} is a factor that considers a reduction of the ultimate tensile strength due to welding processes on aluminium pipes, based on [49]. This factor is equal to 75%.
- F_u is the ultimate tensile strength for aluminium. [N/m^2]
- p_T is the total force by unit length that is applied on the rigid bus. [N/m]
- d_{ext} is the external diameter. [m]

The allowable span for the rigid bus of the substation is the resulting minimum value, given in Equation 7.27.

$$L = min\,(L_v\,,\, L_s) \tag{7.27}$$

Where:

- L is the allowable span. [m]
- L_v is maximum length based on the deflection limit. [m]
- L_s is the maximum length based on the fiber stress. [m]

For an acceptable operation, the condition given in Equation 7.28 has to be fulfilled.

$$\boxed{L_{sp} \leq L} \tag{7.28}$$

Where:

- L_{sp} is the span of the rigid bus, calculated in Subsection 5.2.5. [m]
- L is the allowable span. [m]

7.7 Corona Effect

The corona discharges have to be considered in the design of air insulated buses. The discharges are produced when the bus electric field intensity causes ionization in the air.

As the ozone production and light emissions are unacceptable in some communities, and as corona discharges causes audible noise and can not be eliminated, the right solution is to mitigate and control these discharges to acceptable levels [44].

7.7.1 Voltage gradient by Peek formula

The voltage gradient can be computed by using Equation 7.29. It is a widely used equation that represents the corona onset gradient as a result to empirical studies.

$$E_c = m \cdot E_0 \cdot D_a \left(1 + \frac{C}{\sqrt{D_a \cdot r_{ext}}}\right) \cdot 100000 \tag{7.29}$$

Where:

- E_c is the voltage onset gradient [V/m]
- m is the irregularity factor that takes the surface condition of the conductor into account. Experimental results have shown that the irregularity factor may vary from 0.3 to 0.85 depending on the conductor. A irregularity factor of 0.5 has been considered.
- E_0 is an empirical constant that is equal to 30. [kV/m]
- D_a is the relative density air.
- C is an empirical constant that is equal to 0.301. [1/cm]
- r_{ext} is the external radius of the bus pipe. [m]

The relative density air is calculated using Equation 7.30

$$D_a = \left(\frac{273 + T_0}{273 + T_{amb}}\right) \cdot \left(1 - \frac{H}{10000}\right) \tag{7.30}$$

Where:

- D_a is the relative density air.
- T_0 is the temperature to determine the empirical Peek constants and the irregularity factor. This temperature is 25°C.
- T_{amb} is the ambient temperature. [°C]
- H is the elevation above the sea level. [m]

7.7.2 Determination of the maximum voltage gradient

The maximum voltage gradient at the surface of a three-phase conductor can be estimated using Equation 7.31.

$$E_m = \frac{h_e}{h_e - d_{ext}/2} \cdot E_a \tag{7.31}$$

Where:

- E_m is the average voltage gradient at the surface of the conductor. [V/m]
- h_e is the equivalent distance from the center of the conductor to the ground plane for three phases, given in Equation 7.32. [m]
- d_{ext} is the external diameter of the bus. [m]
- E_a is the average voltage gradient at the surface of the conductor, given in Equation 7.33. [V/m]

$$h_e = \frac{h_{busbar} \cdot d_{busbar}}{\sqrt{4h_{busbar}^2 + d_{busbar}^2}} \tag{7.32}$$

Where:

- h_{busbar} is the height of the bus, calculated in Subsection 5.2.3. [m]
- d_{busbar} is the distance between conductors, calculated in Subsection 5.2.5. [m]

$$E_a = \frac{1.1 \cdot U_{hg}}{\sqrt{3}} \cdot \frac{1}{\frac{d_{ext}}{2} \cdot ln\left(\frac{4\,h_e}{d_{ext}}\right)} \tag{7.33}$$

Where:

- U_{hg} is the high voltage system. [V]

For an acceptable operation, the condition given in Equation 7.34 has to be fulfilled.

$$\boxed{E_m \leq E_c} \tag{7.34}$$

Where:

- E_m is the maximum voltage gradient at the surface of the conductor. [V/m]
- E_c is the voltage onset gradient. [V/m]

7.8 Thermal Expansion

On one hand, the withstand short duration current density caused by the thermal equivalent short circuit current is obtained from Equation 7.35.

$$S_{th} = I_{th}/A_c \tag{7.35}$$

Where:

- S_{th} is the withstand short duration current density. [A/m^2]
- I_{th} is the thermal equivalent short-circuit current, calculated in Section 3.4. [A]
- A_c is the section of the bus. [m^2]

On the other hand and based on [44], the assigned withstand short duration current density is obtained from Equation 7.36.

$$S_{thr} = \sqrt{\frac{1}{T_{kr}} \cdot \frac{\kappa_{20} c \rho}{\alpha_{20}} \cdot \ln\left[\frac{1+\alpha_{20}(\vartheta_e - 20)}{1+\alpha_{20}(\vartheta_b - 20)}\right]} \tag{7.36}$$

Where:

- S_{thr} is the assigned withstand short duration current density. [A/m^2]
- T_{kr} is the short-circuit time given in Section 3.4, which is equal to 1. [s]
- κ_{20} is the aluminium specific conductivity at 20ºC, it is equal to 34800000. [1/Ωm]

- c is the specific thermal capacity and is equal to 910. [J/kg K]
- ρ is the aluminium specific mass and is equal to 2700. [kg/m^3]
- α_{20} is the aluminium temperature coefficient and is equal to 0.004. [1/K]
- ϑ_e is the final temperature of the conductor after the short circuit, and it is equal to 250°C.
- ϑ_b is the initial temperature of the conductor, it is equal to 90°C.

For a safe design, the condition given in Equation 7.37 has to be fulfilled.

$$\boxed{S_{\text{th}} \leq S_{\text{thr}}\sqrt{\frac{T_{\text{kr}}}{T_{\text{k}}}}} \tag{7.37}$$

Where:

- S_{th} is the withstand short-duration current density. [A/m^2]
- S_{thr} is the assigned withstand short-duration current density. [A/m^2]
- T_{k} is the short-circuit duration time. [s]
- T_{kr} is the assigned short-circuit time. [s]

7.9 Selection of the busbar insulator

The outdoor insulators are used primarily to support electrical equipment operating above ground potential. For this purpose, solid core post insulators have been selected as they are the most used type for new substations. In general, the solid core post insulators are made of porcelain and polymer.

Post insulators are characterized by the following:

- Maximum withstand voltage [V].
- Lightning impulse withstand voltage [V].
- Minimum failing load - Bending [N].
- Height.
- Maximum nominal diameter of insulating part.
- Insulator designation: c6-1425 which means that it will not bend up to 6000 N when the lightning impulse is less than 1425 kV.

For a safe design, the condition given in Equation 7.38 has to be fulfilled. In addition, the maximum withstand voltage and the lightning impulse withstand voltage have to be higher than the system voltage and the lightning impulse of the system.

$$\boxed{F_{\text{T}} \leq S_{\text{Bending}}} \tag{7.38}$$

Where:

- F_{T} is the total force on the buses. [N]

Table 7.4: Technical characteristics of post insulators for substations [50]

Insulator designation	Maximum withstand voltage [kV]	Lightning impulse withstand voltage [kV]	Minimum failing load Bending [kN]
c4 - 650	145	650	4
c6 - 650	145	650	6
c8 - 650	145	650	8
c10 - 650	145	650	10
c12.5 - 650	145	650	12.5
c16 - 650	145	650	16
c20 - 650	145	650	20
c>20 - 650	145	650	-

- S_{Bending} is the minimum bending load of the insulator. [N]

As an example, a group of post insulators that belong to the same lightning impulse family are presented in Table 7.4

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Appendix A

Selecting Circuit Arrangements

The installed capacity of a PV plant is 200 MW. The high voltage level is 132 kV and the medium voltage level is 30 kV. In addition, there are 10 lines of 20 MW that connect the plant with the substation.

A.1 Determination of the number of transformer bays

Following Chapter 1, a single busbar substation with two transformer bays is obtained. The following steps have been followed:

First, both high and medium voltage short-circuit currents have been selected. As the high voltage level is 132 kV, the short-circuit current given by Table 3.1 is 40 kA. For the given medium voltage level, the short-circuit current is 25 kA.

If all the medium voltage lines that leave the PV plant were grouped in one transformer, the following results would have been obtained.

- As the power of the bay is 150 MW, per Table 6.1, the short-circuit impedance is 12.5 %. Then, the admissible current of the bay is given by Equation 2.2.

$$I_{\text{des}} = I_{\text{sc}} \cdot z_{\text{cc}} = 25000 \cdot 0.125 = 3150\,A \tag{A.1}$$

- However, the total current of the bay is given by the following equation:

$$I = \frac{S}{\sqrt{3} \cdot U_{\text{mv}}} = \frac{200 \cdot 10^6}{\sqrt{3} \cdot 30000} \approx 3850\,A \tag{A.2}$$

- In this case, only one of the assumptions given in Chapter 2 has been fulfilled. There is one transformer with a short-circuit impedance of 12.5 % but the total current is higher than the admissible current. The reasoning behind this model is the idea that the short-circuit current at the medium voltage level would be higher than the design short-circuit current.

$$\frac{S}{\sqrt{3} \cdot U_{\text{mv}} \cdot z_{\text{cc}}} = \frac{200 \cdot 10^6}{\sqrt{3} \cdot 30000 \cdot 0.125} \approx 30.7kA \geq 25kA \tag{A.3}$$

Then, two 100 MVA transformer bays have been defined.

- As the power of the bays are higher than 63 MW, according to Table 6.1, the short-circuit impedance of every transformer is 12.5 %.

$$z_{\text{sc-1}} = z_{\text{sc-2}} = 12.5\% \tag{A.4}$$

- Then, the admissible current of each transformer bay is calculated by Table 3.1, giving us the following results:

$$I_{\text{adm}} = I_{\text{sc}} \cdot z_{\text{cc}} = 25000 \cdot 0.125 = 3150\, A \tag{A.5}$$

- The total current of each bay is given by the following equations:

$$I_1 = I_2 = \frac{S_1}{\sqrt{3} \cdot U_{\text{mv}}} = \frac{100 \cdot 10^6}{\sqrt{3} \cdot 30000} \approx 1924\, A < 3150\, A \tag{A.6}$$

- The short-circuit current is calculated according to the following formula.

$$\frac{S}{\sqrt{3} \cdot U_{\text{mv}} \cdot z_{\text{cc}}} = \frac{100 \cdot 10^6}{\sqrt{3} \cdot 30000 \cdot 0.125} \approx 15.4kA \leq 25kA \tag{A.7}$$

- After applying the corresponding correction factors to the cables: $3x(4x630mm2)\, Al\, XLPE$, the following results were obtained:

$$I_{\text{op-mv}} \leq I_{\text{ccc}} \Rightarrow 1924\, A < 1925\, A \tag{A.8}$$

In this case, each assumptions given in Chapter 2 have been fulfilled.

Once the number of power transformers has been obtained, the last step is to determine the type of substation (line to transformer, single busbar or double busbar). For that, the total operating current of the PV plant is compared with the maximum admissible current.

$$I_T = \frac{S_T}{\sqrt{3} \cdot U_{\text{mv}}} = \frac{200 \cdot 10^6}{\sqrt{3} \cdot 30000} \approx 3850\, A \leq 3 \cdot I_{\text{des}} = 3 \cdot 3150 = 9450\, A \tag{A.9}$$

Finally, a single busbar substation with two transformer bays is obtained.

A.2 Determination of the number of output bays

The number of output bays will be determined automatically based on only one criterion. This criterion is based on the rated characteristics of the switchgear. So, the criterion that an output bay may fulfil is given in Equation 2.7.

$$I_{\text{op-hv}} = \frac{200 \cdot 10^6}{\sqrt{3} \cdot 132000} \approx 874\, A \leq \frac{4000}{1.25} = 3200\, A \tag{A.10}$$

So, there will be one output bay.

Appendix B

Calculation of the short-circuit currents

In this annex, the main short-circuit current will be determined following the calculation model presented in Chapter 3. The previous example will be taken to study the short-circuit currents:

- The installed capacity of a PV plant is 200 MW.
- The high voltage level is 132 kV and the medium voltage level is 30 kV.
- The frequency of the system is 50 Hz.

B.1 Design short-circuit currents

The design-short circuit currents are obtained directly from the maximum voltage for the system and they are linked to a short-circuit power from the grid.

As the high voltage level is 132 kV, the short-circuit current given by Table 3.1 is 40 kA. For the given medium voltage level, the short-circuit current is 25 kA.

B.2 Operating short-circuit currents

B.2.1 The short-circuit current at the grid level

First, the short-circuit power is taken from Table 3.1. As the voltage is 132 kV, the corresponding short-circuit power is 8000 MVA. At the grid level, only an ideal network contributes to the short circuit.

The internal impedance of a high-voltage network or a medium-voltage network can then be determined according to Equation 3.3.

$$Z_{\text{network}} = \frac{U^2}{S_{sc}} = \frac{145000^2}{8200 \cdot 10^6} = 2.12\,\Omega \tag{B.1}$$

The short-circuit current is calculated according to Equation 3.2

$$I_{\text{op-sc}} = \frac{c \cdot U}{Z \cdot \sqrt{3}} = \frac{1.1 \cdot 132000}{2.12 \cdot \sqrt{3}} \approx 40\,kA \tag{B.2}$$

B.2.2 The short-circuit current at the substation input

First, the short-circuit power is taken from Table 3.1. The internal impedance of a high-voltage network at the medium-voltage level can then be determined according to Equation 3.3.

$$Z_{\text{network}} = \frac{U^2}{S_{\text{sc}}} = \frac{30000^2}{8000 \cdot 10^6} = 0.06\,\Omega \tag{B.3}$$

The impedance of a two-windings transformer is calculated using Equation 3.4.

$$Z_t = \frac{U^2}{S_t} \cdot \frac{z_{\text{sc}}}{100} = \frac{30000^2}{100 \cdot 10^6} \cdot 0.125 = 1.125 \tag{B.4}$$

The short-circuit current is calculated according to Equation 3.2

$$I_{\text{op-sc}} = \frac{c \cdot U}{Z \cdot \sqrt{3}} = \frac{1.1 \cdot 30000}{(0.06 + 1.125) \cdot \sqrt{3}} = 16\,kA \tag{B.5}$$

B.3 Peak short-circuit currents

The factor κ shall be obtained from Equation 3.6.

$$\kappa = 1.02 + 0.98e^{(-3R/X)} = 1.81 \tag{B.6}$$

The peak short-circuit current can be calculated using Equation 3.5.

$$I_p = I_{\text{op-sc}} \cdot \kappa \sqrt{2} = 40 \cdot 1.81 \sqrt{2} = 102.36\,kA \tag{B.7}$$

The peak short-circuit current can be calculated using Equation 3.5.

$$I_p = I_{\text{op-sc}} \cdot \kappa \sqrt{2} = 16 \cdot 1.81 \sqrt{2} = 41\,kA \tag{B.8}$$

B.4 Thermal short-circuit currents

The factor m shall be obtained from Equation 3.8.

$$m = \frac{1}{2 \cdot f \cdot T_k \cdot ln(\kappa - 1)} \cdot \{e^{4 \cdot f \cdot T_k \cdot ln(\kappa - 1)} - 1\} = 0.048 \tag{B.9}$$

The thermal equivalent short-circuit current can be calculated using Equation 3.7.

$$I_{\text{th}} = I_{\text{op-sc}}\sqrt{m+n} = 40\sqrt{1.048} = 41\,kA \tag{B.10}$$

The thermal equivalent short-circuit current can be calculated using Equation 3.7.

$$I_{\text{th}} = I_{\text{op-sc}}\sqrt{m+n} = 16\sqrt{1.048} = 16\,kA \tag{B.11}$$

Appendix C

Insulation Coordination

For the substation that has been proposed in these annexes, the insulation coordination results are presented in this chapter. The example has the following inputs:

- The high voltage system that equals 132 kV.
- The elevation above the sea level that equals 550 m.

The results that will be validated are the following ones:

- The rated lightning impulse withstand voltage that is equal to 550 kV.
- The phase-to-earth short-duration power-frequency withstand voltage equals 185 kV.
- The phase-to-phase short-duration power-frequency withstand voltage equals 275 kV.
- The phase-to-earth clearance distance that equals 1.1 m.
- The phase-to-phase clearance distance that equals 1.1 m.

C.1 General procedure for insulation coordination

As the high voltage of the system (132 kV) is lower than 245 kV, the class I substation procedure is followed. The highest voltage for the equipment is 145 kV as given in Table 4.1.

C.1.1 Class I insulation coordination procedure

To establish a minimum recommended phase-to-earth and phase-to-phase clearance distances, the following steps are necessary:

1. Determination of the representative temporary, slow-front, and fast-front overvoltages.
2. Application of the coordination factor to set the coordination overvoltages.
3. Calculation of the required overvoltages by applying a security factor and the atmospheric correction factors.
4. Conversion of the slow-front overvoltages to temporary and fast-front overvoltages by applying conversion factors.
5. Identification and selection of the standard rated withstand voltages in regards to the required overvoltages by referring to the highest voltages for the equipment.

6. If some required voltages are higher than the maximum standard rated withstand voltage for a specific highest voltage for equipment, a greater value of the standard voltage is selected even though the highest voltage is superior.
7. Selection of the minimum rod-structure and conductor-structure clearance distances for the standard rated withstand voltages that have been selected.
8. Identification of the phase-to-earth and phase-to-phase distances.

C.2 Determination of the representative voltages and overvoltages

C.2.1 Temporary overvoltages

For voltage systems higher than 36 kV, the maximum representative phase-to-earth and phase-to-phase overvoltages are calculated using Equation 4.1 and Equation 4.2

$$U_{\text{temp-rp-pe}} = \frac{k_{\text{max}} \cdot U_{\text{m}}}{\sqrt{3}} = \frac{1.4 \cdot 145}{\sqrt{3}} = 117.2\,kV \tag{C.1}$$

$$U_{\text{temp-rp-pp}} = k_{\text{d}} \cdot U_{\text{m}} = 1.4 \cdot 145 = 203\,kV \tag{C.2}$$

C.2.2 Slow-front overvoltages

The value of the phase-to-earth overvoltage that has a 2% of probabilities of being exceeded is $u_{e2} = 2.6$ p.u. The phase-to-phase overvoltage that has 2% of probabilities of being exceeded is given in Figure 4.2 and in our case, it equals $u_{p2} = 3.78$ p.u.

The phase-peak method has been chosen to calculate the truncation values using Equation 4.5 and Equation 4.6.

$$u_{\text{et}} = 1.25 \cdot u_{\text{e2}} - 0.25 = 1.25 \cdot 2.6 - 0.25 = 3\,p.u. \tag{C.3}$$

$$u_{\text{pt}} = 1.25 \cdot u_{\text{p2}} - 0.43 = 1.25 \cdot 3.8 - 0.43 = 4.3\,p.u. \tag{C.4}$$

The parts per one are converted to volts following the Equation 4.7

$$u_{\text{et}} = \sqrt{\frac{2}{3}} \cdot 145 \cdot 3 = 355\,kV \tag{C.5}$$

$$u_{\text{pt}} = \sqrt{\frac{2}{3}} \cdot 145 \cdot 4.3 = 509\,kV \tag{C.6}$$

Determination of the switching impulse protective level

As the lightning arrester has been chosen following the process in section 6.3.1, the switching impulse protective level equals $U_{\text{ps}} = 272$ kV.

To obtain the representative overvoltages for slow-front impulses, Equation 4.8 and Equation 4.9 are used.

$$U_{\text{sf-rp-pe}} = min\ (U_{\text{ps}}\,,\ U_{\text{et}}) = min\ (272\,,\ 355) = 272\,kV \tag{C.7}$$

$$U_{\text{sf-rp-pe}} = min\ (2 \cdot U_{\text{ps}}\,,\ U_{\text{pt}}) = min\ (544\,,\ 509) = 509\,kV \tag{C.8}$$

C.2.3 fast-front overvoltages

For fast-front overvoltages, the coordination withstand overvoltages will be directly computed in Subsection C.3.3.

C.3 Determination of the coordination withstand voltages

According to [11], a deterministic approach will be adopted to determine the coordination overvoltages.

C.3.1 Temporary overvoltages

For the temporary overvoltages, the coordination factor is equal to one. Hence, the representative overvoltages and the coordination overvoltages are equal. The calculation of the phase-to-earth and phase-to-phase temporary overvoltages are represented by Equation 4.10 and Equation 4.11 respectively.

$$U_{\text{temp-cw-pe}} = k_{\text{cd}} \cdot U_{\text{temp-rp-pe}} = 1 \cdot 117.2 = 117.2\,kV \tag{C.9}$$

$$U_{\text{temp-cw-pp}} = k_{\text{cd}} \cdot U_{\text{temp-rp-pp}} = 1 \cdot 203 = 203\,kV \tag{C.10}$$

C.3.2 Slow-front overvoltages

The coordination factor is obtained from Figure 4.3. The coordination slow-front overvoltages are obtained from Equation 4.12 and Equation 4.13.

$$U_{\text{sf-cw-pe}} = k_{\text{cd-pe}} \cdot U_{\text{sf-rp-pe}} = 1.06 \cdot 272 = 289\,kV \tag{C.11}$$

$$U_{\text{sf-cw-pp}} = k_{\text{cd-pp}} \cdot U_{\text{sf-rp-pp}} = 1 \cdot 509 = 509\,kV \tag{C.12}$$

C.3.3 Fast-front overvoltages

According to [14], the probability values that are needed to calculate the coordination overvoltages can be found in Table 4.3. For the 132 kV substation, these values are:

- A = 4500 kV.
- f_s = 0.5.
- N = 1.
- L_t = 30 m.

- $L_{sp} = 300$ m.
- $L_f = 0.25/0.001 = 250$ m. [m]

The lightning impulse protective level of the lightning arrester that was computed in Section E.3 is $U_{pl} = 311$ kV. The coordination overvoltages for fast-front impulses proceed as given in Equation 4.14.

$$U_{\text{ff-cw}} = U_{pl} + \frac{A \cdot f_s}{N} \cdot \frac{L_t}{L_{sp} + L_f} = 311 + \frac{4500 \cdot 0.5}{1} \cdot \frac{30}{300 + 250} = 311 + 122 = 433\,kV \tag{C.13}$$

C.4 Determination of the required withstand voltages

The safety correction factors that apply to each kind of overvoltage are given in Equation 4.16 and Equation 4.17 respectively.

$$K_{si} = 1.15 \tag{C.14}$$

$$K_{se} = 1.05 \tag{C.15}$$

Moreover, the atmospheric correction factor for temporary and fast-front overvoltages can be calculated using Equation 4.18.

$$K_a = \exp\left(m \cdot \frac{H}{8150}\right) = \exp\left(0.5 \cdot \frac{550}{8150}\right) = 1.03 \tag{C.16}$$

For slow-front overvoltages, the coefficient m is defined according to Figure 4.4.

$$K_{\text{a-pe}} = \exp\left(m \cdot \frac{H}{8150}\right) = \exp\left(1 \cdot \frac{550}{8150}\right) = 1.07 \tag{C.17}$$

$$K_{\text{a-pp}} = \exp\left(m \cdot \frac{H}{8150}\right) = \exp\left(1 \cdot \frac{550}{8150}\right) = 1.07 \tag{C.18}$$

Required temporary overvoltages

$$U_{\text{temp-pe-i-rw}} = 117.2 \cdot 1.15 = 134\,kV \tag{C.19}$$

$$U_{\text{temp-pe-e-rw}} = 117.2 \cdot 1.05 \cdot 1.03 = 126\,kV \tag{C.20}$$

$$U_{\text{temp-pp-i-rw}} = 203 \cdot 1.15 = 233\,kV \tag{C.21}$$

$$U_{\text{temp-pp-e-rw}} = 203 \cdot 1.05 \cdot 1.03 = 219\,kV \tag{C.22}$$

Required slow-front overvoltages

$$U_{\text{sf-pe-i-rw}} = 289 \cdot 1.15 = 332\, kV \tag{C.23}$$

$$U_{\text{sf-pe-e-rw}} = 289 \cdot 1.05 \cdot 1.07 = 324\, kV \tag{C.24}$$

$$U_{\text{sf-pp-i-rw}} = 509 \cdot 1.15 = 585\, kV \tag{C.25}$$

$$U_{\text{sf-pp-e-rw}} = 509 \cdot 1.05 \cdot 1.07 = 572\, kV \tag{C.26}$$

Required fast-front overvoltages

$$U_{\text{ff-pe-i-rw}} = 433 \cdot 1.15 = 498\, kV \tag{C.27}$$

$$U_{\text{ff-pe-e-rw}} = 433 \cdot 1.05 \cdot 1.03 = 487\, kV \tag{C.28}$$

$$U_{\text{ff-pp-i-rw}} = 433 \cdot 1.15 = 498\, kV \tag{C.29}$$

$$U_{\text{ff-pp-e-rw}} = 433 \cdot 1.05 \cdot 1.03 = 487\, kV \tag{C.30}$$

C.5 Selection of the rated insulation levels

In order to obtain the withstand voltages that are recommended for the standard, the maximum required withstand voltages will be considered.

- The phase-to-earth temporal overvoltage that is considered is 134 kV.
- The phase-to-phase temporal overvoltage that is taken into account is 233 kV.
- The fast-front overvoltage that is considered is 498 kV.

The standard withstand voltages for class I (145 kV) substation can be found in Table 4.6.

- The phase-to-earth short-duration power-frequency withstand voltage is 185 kV.
- The phase-to-phase short-duration power-frequency withstand voltage is 275 kV.
- The standard rated lightning impulse withstand voltage is 550 kV.

C.6 Selection of the clearance distances

The tables 4.8, 4.9, and 4.10 present the minimum clearances that ensure the specifications of the insulation coordination.

- As the standard rated lightning impulse withstand voltage is 550 kV, the rod-structure is 1.1 m.
- For 550 kV lightning impulse withstand voltage, a value of 1.1 m of conductor-structure clearance is taken.

The phase-to-earth and phase-to-phase air distances are calculated using Equation 4.20 and Equation 4.21.

$$d_{\text{pe}} = min\left(d_{\text{rod-str}}\,,\, d_{\text{cond-str}}\right) = min\left(1.1\,,\, 1.1\right) = 1.1\, m. \tag{C.31}$$

$$d_{\text{pp}} = d_{\text{rod-str}} = 1.1\, m. \tag{C.32}$$

Appendix D

Safety Distances

For the substation that has been proposed in these annexes, the safety distances are presented in this chapter. The example has the following inputs:

- The rated lightning impulse withstand voltage that is equal to 550 kV.
- The phase-to-earth clearance distance that equals 1.1 m.
- The phase-to-phase clearance distance that equals 1.1 m.

The results that will be validated are the following ones:

- A distance between conductors of 3 m.
- A lengthwise distance between elements of the switchgear of 3 m.
- A busbar/gateway span of 12 m.
- A device height of 3.5 m.
- A busbar height of 6.5 m.
- A gateway height of 9.5 m.

D.1 General procedure for the calculation of the safety distances

D.1.1 The basic value

The basic value is calculated using Equation 5.1. The factor corresponds to 1.1 if the impulse withstand voltage ≤ 1425 kV and 1.06 if it is > 1425 kV.

$$d_{\text{bv}} = f_{\text{bv}} \cdot d_{\text{pe}} = 1.1 \cdot 1.1 = 1.21\, m. \tag{D.1}$$

D.1.2 Field height

The three height limits given by Equation 5.2, Equation 5.3, and Equation 5.4.

$$h_{\text{device}} = d_{\text{bv}} + H_{\text{r}} = 1.21 + 2.25 = 3.5\, m \tag{D.2}$$

For the busbar height, the additional distance $d_{\text{bv}} + H_{\text{rw}}$ should be studied. So, $d_{\text{bv}} + H_{\text{rw}} = 1.21 + 1.25 = 2.46 < 3\,m$.

$$h_{\text{busbar}} = h_{\text{device}} + d_{\text{bv}} + H_{\text{rw}} = 3.5 + 3 = 6.5\,m. \tag{D.3}$$

For the gateway height, the additional distance $d_{\text{bv}} + H_{\text{rw}}$ should be studied. So, $d_{\text{bv}} + H_{\text{rw}} = 1.21 + 1.25 = 2.46 < 3\,m$.

$$h_{\text{overhead line}} = h_{\text{busbar}} + d_{\text{bv}} + H_{\text{rw}} = 6.5 + 3 = 9.5\,m. \tag{D.4}$$

D.1.3 Field length

An estimation of the safety distance from the extreme position that the live equipment or conductor may occupy is derived from Equation 5.5.

$$l_{\text{device}} = max(d_{\text{bv}} + L_{\text{o}}\,,\, d_{\text{pp}}) = max(1.21 + 1.75\,,\, 1.1) = 2.96 < 3 \Rightarrow 3\,m. \tag{D.5}$$

D.1.4 Distance between buses

The distance between conductors is defined using Equation 5.6.

$$d_{\text{bus}} = max(d_{\text{bv}} + L_{\text{o}}\,,\, d_{\text{pp}}) = max(1.21 + 1.75\,,\, 1.1) = 2.96 < 3 \Rightarrow 3\,m. \tag{D.6}$$

Once the distance between conductors has been established, the busbar/gateway span is derived from Equation 5.7.

$$d_{\text{span}} = 2 \cdot d_{\text{bus}} + 2 \cdot d_{\text{bus-support}} = 2 \cdot 3 + 2 \cdot 3 = 12m. \tag{D.7}$$

Appendix E

Determination of the substation's equipment

For the substation that has been proposed in these annexes, in this chapter the main characteristics of each equipment of a transformer bay are presented. The example has the following inputs:

- The high voltage that equals 132 kV and the short-circuit current for this level is 40 kA.
- The medium voltage that equals 30 kV and the short-circuit current for this level is 25 kA.
- The total power of the transformer bay is 100 MW.
- The frequency of the system is equal to 50 Hz.

E.1 Determination of the power transformer

Following Section 6.1, the power transformer of the bay will have the following characteristics.

- The transformer capacity is 100 MVA which equals the power of the bay.
- The voltage ratio is 132/30 kV.
- The vector group is Ynd11.
- The short-circuit impedance is 12.5 % according to Table 6.1.

E.2 Determination of the grounding device

The short-circuit current at the secondary winding of the transformer is 25 kA. The current that flows through the neutral point of the zig-zag transformer is given by Equation 6.1.

$$I_{\text{zig-zag}} = 0.03 \cdot I_{\text{sc}} = 0.03 \cdot 25000 = 750\,A \tag{E.1}$$

As 750 A is not contemplated as standard value by the software, the current taken is 800 A.

The phase reactance of the transformer is presented in Equation 6.2.

$$X_g = \frac{X_0/X_1 \cdot U_{mv}}{\sqrt{3} \cdot I_{sc}} = \frac{10 \cdot 30000}{\sqrt{3} \cdot 25000} = 6.93\Omega \tag{E.2}$$

The earthing resistance is obtained using Equation 6.3.

$$R_g = \frac{U_{mv}}{\sqrt{3} \cdot I_{zig\text{-}zag}} = \frac{30000}{\sqrt{3} \cdot 800} = 21.65\Omega \tag{E.3}$$

E.3 Determination of the surge arrester

The calculation model to size a surge arrester is presented in Section 6.3. In order to compute the surge arrester which is located at the high voltage level, it is necessary to get the highest voltage for the system. By 4.1, this voltage equals 145 kV.

First, the continuous operating voltage is obtained, using Equation 6.4.

$$U_{cov} \geq \frac{f_{cov} \cdot U_m}{\sqrt{3}} = \frac{1.1 \cdot 145000}{\sqrt{3}} = 92\,kV \tag{E.4}$$

The next step is to get the temporary overvoltage for the lightning arrester using Equation 6.5

$$U_{tov} \geq f_{tov} \cdot U_{cov} = 1.4 \cdot 92 = 128.9\,kV \tag{E.5}$$

The temporary overvoltages based on the equivalent 10 seconds duration overvoltage is calculated using Equation 6.6.

$$U_{10s} = U_{tov} \cdot \left(\frac{\tau}{10}\right)^{\eta} = 128.9 \cdot \left(\frac{1}{10}\right)^{0.02} = 123\,kV \tag{E.6}$$

The rated voltage is given in Equation 6.7.

$$U_r = max\,(1.25 \cdot U_{cov}\,,\ U_{10s}) = max\,(1.25 \cdot 92\,,\ 123) = max\,(115\,,\ 123) = 123\,kV \tag{E.7}$$

The nominal discharge current is $I_{nom} = 10$ kA due to $U_m = 145 < 360$ kV.

The characteristics already mentioned are not applicable for commercial purposes. For that reason, a database of commercial surge arresters has been added to the software. The selected surge arrester is presented in Table E.1 and it has the following characteristics:

- The rated voltage is 132 kV.
- The continuous operation voltage is 92 kV.
- The temporary overvoltage is 145 kV.
- As the nominal discharge current is 10 kA, the lightning impulse protection level is 311 kV.
- The lightning impulse protection level is 272 kV.

Table E.1: Technical data for surge arresters - 145 kV. [22], [25] and [26]

Highest voltage for equipment U_m [kV]	U_r [kV]	U_{cov} [kV]	U_{tov} [kV]	U_{ps} [kV]	$U_{pl\text{-}10kA}$ [kV]	$U_{pl\text{-}20kA}$ [kV]
145	114	91	125	235	268	295
145	120	92	132	248	282	311
145	132	92	145	272	311	342
145	138	92	151	285	325	357
145	144	92	158	297	339	373
145	150	92	165	309	353	388
145	162	92	178	334	381	419
145	168	92	184	346	395	435
145	180	92	198	371	423	466

E.4 Circuit breakers

The main characteristics are defined according to [27], [28] and [29]. The most important rating is the rated normal current that is calculated based on [31].

The rated voltage of the circuit breaker is given by Equation 6.8.

$$U_{cb} = U_m = 145\ kV \tag{E.8}$$

The rated normal current is calculated by Equation 6.9. It is recommended to select 1600 A for short-circuit currents of 40 kA.

$$I_{cb} = \frac{f_s \cdot P}{U \cdot \sqrt{3}} = \frac{1.25 \cdot 100 \cdot 10^6}{132 \cdot 10^3 \cdot \sqrt{3}} = 546\ A \Rightarrow 1600\ A \tag{E.9}$$

The rated short-circuit breaking current is calculated by Equation 6.10.

$$I_{sc\text{-}cb} = I_{sc} = 40\ kA \tag{E.10}$$

The rated short-circuit making current is given by Equation 6.11.

$$I_{msc\text{-}cb} = f_{msc} \cdot I_{sc\text{-}cb} = 2.5 \cdot 40 = 100\ kA \tag{E.11}$$

E.5 Disconnectors

The rated voltage is given by Equation 6.12.

$$U_d = U_m = 145\ kV \tag{E.12}$$

The rated normal current is calculated by Equation 6.13. It is recommended to select 1600 A for short-circuit currents of 40 kA.

$$I_{\text{d}} = \frac{f_{\text{s}} \cdot P}{U \cdot \sqrt{3}} = \frac{1.25 \cdot 100 \cdot 10^6}{132 \cdot 10^3 \cdot \sqrt{3}} = 546\,A \Rightarrow 1600\,A \tag{E.13}$$

The rated short-time withstand current is calculated by Equation 6.14.

$$I_{\text{sc-d}} = I_{\text{sc}} = 40\,kA \tag{E.14}$$

The rated peak withstand current is given in Equation 6.15.

$$I_{\text{psc-d}} = f_{\text{psc}} \cdot I_{\text{sc-cb}} = 2.5 \cdot 40 = 100\,kA \tag{E.15}$$

E.6 Current transformers

The rated voltage is given by Equation 6.16.

$$U_{\text{ct}} = U_{\text{m}} = 145\,kV \tag{E.16}$$

The rated secondary current is equal to 5 A. The rated primary current is calculated by Equation 6.17. After obtaining the current, the closest standard current will be selected. [34]. In this case, The R10 values are not followed.

$$I_{\text{ct}} = \frac{f_{\text{s}} \cdot P}{U \cdot \sqrt{3}} = \frac{1.25 \cdot 100 \cdot 10^6}{132 \cdot 10^3 \cdot \sqrt{3}} = 546\,A \Rightarrow 600\,A \tag{E.17}$$

The rated continuous thermal current is given by Equation 6.18.

$$I_{\text{t}} = I_{\text{ct}} = 600\,A \tag{E.18}$$

The rated short-time thermal current is given by Equation 6.19.

$$I_{\text{sc-ct}} = I_{\text{sc}} = 40\,kA \tag{E.19}$$

The dynamic current is calculated using Equation 6.20.

$$I_{\text{dyn}} = f_{\text{dyn}} \cdot I_{\text{sc-ct}} = 2.5 \cdot 40 = 100\,kA \tag{E.20}$$

E.7 Voltage transformers

The primary voltage is the voltage of the system, given in Equation 6.21

$$U_{\text{vt}} = \frac{U}{\sqrt{3}} = \frac{132}{\sqrt{3}}\,kV \tag{E.21}$$

E.8 Capacitor Bank

The following characteristics have been used to size the capacitor bank:

- The rated medium voltage is 30 kV.
- The required reactive compensation is 2 MVAr.
- The detuned factor is equal to 7 % .

First, the reactances of the capacitor and the detuned reactor are calculated.

According to Equation 6.22, the total reactance of the capacitor feeder is calculated as:

$$X_T = \frac{U^2}{Q_{req}} = \frac{30000^2}{2 \cdot 10^6} = 450\ \Omega \tag{E.22}$$

The reactance of the capacitor is then calculated using Equation 6.23:

$$X_C = \frac{X_T}{1 - (D_f/100)} = \frac{450}{1 - (7/100)} = 483.87\ \Omega \tag{E.23}$$

The detuned reactor's reactance is calculated as a fraction of the capacitor bank's reactance from Equation 6.24:

$$X_L = X_C \cdot (D_f/100) = 483.87 \cdot (7/100) = 33.87\ \Omega \tag{E.24}$$

Now, the current and voltages at different points of the capacitor feeder are calculated.

Equation 6.25 is used to obtain the current flowing through the capacitor feeder:

$$I_{cap} = \frac{Q_{req}}{\sqrt{3} \cdot U} = \frac{2 \cdot 10^6}{\sqrt{3} \cdot 30000} = 38.49\ A \tag{E.25}$$

The voltage across the detuned reactor is computed using Equation 6.26:

$$U_L = \sqrt{3} \cdot I_{cap} \cdot X_L = \sqrt{3} \cdot 38.49 \cdot 33.87 = 2258\ V \tag{E.26}$$

Two voltages at the capacitor bank are calculated. One without over-voltage and one with an over-voltage factor of 1.1. For this, Equation 6.27 is used:

$$U_{C_{c=1}} = U + U_L = 30000 + 2258 = 32258\ V \tag{E.27}$$

$$U_{C_{c=1.1}} = cU + U_L = 1.1 \cdot 30000 + 2258 = 35258\ V \tag{E.28}$$

Finally, the reactive power that will be generated by the capacitor bank and the reactive power consumed by the detuned reactor can be calculated from Equation 6.28 and Equation 6.29 respectively:

$$Q_C = \frac{U_{C_{c=1}}^2}{X_C} = \frac{32258^2}{483.87} = 2.15\,MVAr \tag{E.29}$$

$$Q_L = \frac{U_L^2}{X_L} = \frac{2258^2}{33.87} = 0.15\,MVAr \tag{E.30}$$

The summation of Q_C and Q_L should be equal to the desired compensation:

$$Q_T = Q_C - Q_L = 2.15 - 0.15 = 2MVAr \tag{E.31}$$

Appendix F

Design of the bus in air insulated substations

F.1 Introduction

The following example clarifies the process of designing a rigid busbar for an air-insulated substation using the information presented in [44] and [45]. The parameters required for the bus design are:

- The installed capacity of the photovoltaic plant, $P_{\text{ac}} = 200\,MW$
- The high voltage level $U_{\text{hg}} = 132\,kV$
- The number of transformer bays $n_{\text{Tr}} = 2$
- The span of the rigid bus $L_{\text{sp}} = 12\,m$
- The distance between conductors, $d_{\text{bus}} = 3\,m$
- The height of the bus $h_{\text{busbar}} = 6.5\,m$
- The rated lightning impulse withstand voltage, $U_{\text{liwv}} = 550\,kV$
- The design short-circuit current, $I_{\text{sc}} = 40\,kA$
- The frequency of the system, $f = 50\,Hz$
- The ambient temperature, $T_{\text{amb}} = 25\,°\text{C}$
- The elevation above the sea, $H = 550\,m$

The results that will be validated are the following ones:

- The external diameter equals 150 mm.
- The external diameter equals 134 mm.
- The post insulator is c10-650.

F.2 Specific properties of the buses

More information about the bus can be found in Table 7.1. The section of the bus is obtained from Equation 7.1.

$$A_c = \pi \cdot \frac{d_{ext}^2 - d_{int}^2}{4} = \pi \cdot \frac{0.15^2 - 0.134^2}{4} = 3562\, mm^2 \tag{F.1}$$

The moment of resistance of the pipe is calculated using Equation 7.2

$$S_c = \pi \cdot \frac{d_{ext}^4 - d_{int}^4}{32 \cdot d_{ext}} = \pi \cdot \frac{0.15^4 - 0.134^4}{32 \cdot 0.15} = 1.2 \cdot 10^{-4}\, m^3 \tag{F.2}$$

The moment of inertia is obtained using Equation 7.3

$$I = \pi \cdot \frac{d_{ext}^4 - d_{int}^4}{64} = \pi \cdot \frac{0.15^4 - 0.134^4}{64} = 9.02 \cdot 10^{-6}\, m^4 \tag{F.3}$$

The unitary weight of the pipe is represented by Equation 7.4

$$u_{bus} = w_{Al} \cdot A_c = 2700 \cdot 3562/10^{-6} = 9.63\, kg/m \tag{F.4}$$

Other significant technical properties are:

- E is the modulus of elasticity for aluminium, which is equal to 7 $\cdot 10^{10}$ [N/m^2].
- F_u is the ultimate tensile strength for aluminium that is equal to 220 $\cdot 10^6$ [N/m^2].
- F_y is the tensile yield strength for aluminium that is equal to 185 $\cdot 10^6$ [N/m^2].
- α_c is the coefficient temperature expansion, which is equal to 0.023 [mm/m°C].

F.3 Minimum size for load current

The load current carried by the bus is calculated using Equation 7.5.

$$I_{load} = \frac{f_{growth} \cdot P_{ac}}{U_{hg} \cdot \sqrt{3}} = \frac{1.25 \cdot 200 \cdot 10^6}{132000 \cdot \sqrt{3}} = 1093\, A \tag{F.5}$$

The condition given in Equation 7.6 is fulfilled.

$$I_{load} = 1093\, A \leq A_{bus} = 4838\, A \tag{F.6}$$

F.4 Minimum size for short-circuit current

The bus conductor should be able to withstand a short-circuit current [44], given by Equation 7.7 for a short period of time.

$$I_{bus\ sc} = C \cdot 10^{12} \cdot A_c \sqrt{\frac{1}{t} \cdot \log_{10}\left(\frac{T_f - 20 + 15150/G}{T_i - 20 + 15150/G}\right)} = 319\, kA \tag{F.7}$$

The condition given in Equation 7.8 is fulfilled.

$$I_{sc} = 40\,kA \leq I_{bus\ sc} = 319\,kA \tag{F.8}$$

F.5 Rigid bus loads

F.5.1 Calculation of the forces by unit length applied on the bus

The maximum force by unit length on the conductor should first be determined.

The weight force by unit length on the bus is given by Equation 7.9.

$$p_{weight} = \left(u_{bus} + u_{damper}\right) \cdot g = u_{bus} \cdot C_{damper} \cdot g = 9.63 \cdot 1.25 \cdot 9.8 = 118\,N/m \tag{F.9}$$

The ice force by unit length on the bus is calculated based on [47].

$$p_{ice} = 1.8\sqrt{d_{ext}} = 1.8\sqrt{0.15} = 0.69\,N/m \tag{F.10}$$

The maximum short circuit force by unit length on the buses is obtained according to Equation 7.10.

$$p_{m3} = \frac{\mu_0}{2\pi}\frac{\sqrt{3}}{2}\frac{1}{d_{pp}}I^2_{peak} = \frac{\mu_0}{2\pi}\frac{\sqrt{3}}{2}\frac{1}{3}102360^2 = 608\,N/m \tag{F.11}$$

The wind force by unit length on the busbar surfaces is calculated using Equation 7.11.

$$p_{wind\text{-}busbar} = d_{ext} \cdot P_{air} \cdot \left(\frac{V_{wind}}{V_{ref}}\right)^2 = 0.15 \cdot 700 \cdot \left(\frac{120}{120}\right)^2 = 105\,N/m \tag{F.12}$$

The wind force by unit length on the c10-650 post insulator, whose external diameter is 0.4 m, is calculated using Equation 7.11.

$$p_{wind\text{-}postInsulator} = d_{ext} \cdot P_{air} \cdot \left(\frac{V_{wind}}{V_{ref}}\right)^2 = 0.4 \cdot 700 \cdot \left(\frac{120}{120}\right)^2 = 280\,N/m \tag{F.13}$$

F.5.2 Reactions

The bus-support conditions depend on the number of transformer bays. Hence, the effective conductor span length L_E is obtained using Equation 7.12.

$$L_E = C_{reaction} \cdot L_{sp} = 1.25 \cdot 12 = 15\,m \tag{F.14}$$

The reactions on the supports due to the weight is obtained using Equation 7.13

$$F_{\text{w}} = p_{\text{w}} \cdot L_{\text{e}} = 118 \cdot 15 = 1770\,N \tag{F.15}$$

The reactions on the supports due to the ice is obtained using Equation 7.13

$$F_{\text{ice}} = p_{\text{ice}} \cdot L_{\text{e}} = 0.69 \cdot 15 = 10.35\,N \tag{F.16}$$

The reactions on the supports due to the wind on the busbars is obtained using Equation 7.13

$$F_{\text{wind-busbar}} = p_{\text{wind-busbar}} \cdot L_{\text{e}} = 105 \cdot 15 = 1575\,N \tag{F.17}$$

The reactions on the supports caused by the short-circuit current forces by unit length are obtained using Equation 7.14

$$F_{\text{sc}} = p_{\text{r}} \cdot L_{\text{e}} = 1.69 \cdot 0.51 \cdot 608 \cdot 15 = 7890\,N \tag{F.18}$$

The reactions on the bus supports caused by wind force on the insulators, whose length is 1.5 m, are obtained using Equation 7.16.

$$F_{\text{wind insulator}} = p_{\text{wind insulator}} \cdot C_{\text{reaction insulator}} \cdot L_{\text{insulator}} = 280 \cdot 0.625 \cdot 1.5 = 262\,N/m \tag{F.19}$$

The total force on the bus supports is the results of the vector sum of all forces as shown in Equation 7.17

$$F_{\text{T}} = \sqrt{(F_{\text{w}} + F_{\text{ice}})^2 + (F_{\text{sc}} + F_{\text{wind-busbar}} + F_{\text{wind insulator}})^2} = 9974\,N \tag{F.20}$$

F.5.3 Stresses on bus

The stresses on the bus caused by weight forces are obtained using Equation 7.20.

$$\sigma_{\text{weight}} = \frac{p_{\text{weight}} \cdot C_{\text{stress}} \cdot L_{\text{sp}}^2}{S_{\text{c}}} = \frac{118 \cdot 0.07 \cdot 12^2}{S_{\text{c}}} \approx 10\,N/mm^2 \tag{F.21}$$

The stresses on the bus caused by ice forces are obtained using Equation 7.20.

$$\sigma_{\text{ice}} = \frac{p_{\text{ice}} \cdot C_{\text{stress}} \cdot L_{\text{sp}}^2}{S_{\text{c}}} = \frac{0.69 \cdot 0.07 \cdot 12^2}{S_{\text{c}}} \approx 0\,N/mm^2 \tag{F.22}$$

The stresses on the bus caused by wind forces are obtained using Equation 7.20.

$$\sigma_{\text{wind-busbar}} = \frac{p_{\text{wind-busbar}} \cdot C_{\text{stress}} \cdot L_{\text{sp}}^2}{S_{\text{c}}} = \frac{105 \cdot 0.07 \cdot 12^2}{S_{\text{c}}} \approx 9\,N/mm^2 \tag{F.23}$$

To obtain the mechanical stress on the bus caused by the short circuit load, the IEC standard [45] has been followed and Equation 7.21 has been used.

$$\sigma_{\text{sc}} = \frac{V_\sigma \cdot V_{\text{r}} \cdot \beta \cdot p_{\text{r}} \cdot L_{\text{sp}}^2}{8S_{\text{c}}} = \frac{0.46 \cdot 1.8 \cdot 0.73 \cdot 531 \cdot 12^2}{8S_{\text{c}}} \approx 45\, N/mm^2 \tag{F.24}$$

The stress on the bus caused by the wind force on the insulator is obtained using Equation 7.22.

$$\sigma_{\text{wind insulator}} = \frac{p_{\text{wind}} \cdot C_{\text{stress insulator}} \cdot L_{\text{insulator}}^2}{S_{\text{insulator}}} \approx 0\, N/mm^2 \tag{F.25}$$

The total force on the bus supports is the result of the vector sum of all the forces as shown in Equation 7.24

$$\sigma_{\text{T}} = \sqrt{\left(\sigma_{\text{weigth}} + \sigma_{\text{ice}}\right)^2 + \left(\sigma_{\text{sc}} + \sigma_{\text{wind-busbare}} + \sigma_{\text{wind insulator}}\right)^2} \approx 55\, N/mm^2 \tag{F.26}$$

The condition given in Equation 7.18 is fulfilled.

$$\sigma_{\text{T}} \approx 55\, N/mm^2 \leq q \cdot F_{\text{y}} = 1.34 \cdot 185 = 248\, N/mm^2 \tag{F.27}$$

Where:

$$q = 1.7 \frac{1 - (1 - 2t/d_{\text{ext}})^3}{1 - (1 - 2t/d_{\text{ext}})^4} = 1.34 \tag{F.28}$$

F.6 Allowable Span

The maximum length based on the deflection limit of the aluminium is calculated using the Equation 7.25.

$$L_{\text{v}} = \left(\frac{185 \cdot E \cdot I \cdot f_{\text{def}}}{p_{\text{g}}}\right)^{\frac{1}{3}} = \left(\frac{185 \cdot E \cdot I \cdot 0.0033}{118}\right)^{\frac{1}{3}} = 14.83\, m \tag{F.29}$$

The allowable span based on the fibre stress is obtained using the Equation 7.26.

$$L_{\text{s}} = \sqrt{\frac{16 \cdot I \cdot f_{\text{weld}} \cdot F_{\text{u}}}{p_{\text{T}} \cdot d_{\text{ext}}}} = \sqrt{\frac{16 \cdot I \cdot 0.75 \cdot F_{\text{u}}}{1000 \cdot 0.15}} = 12.6\, m \tag{F.30}$$

The allowable span for the rigid bus of the substation is the resulting minimum value, given in Equation 7.27.

$$L = min\,(14.83\,,\ 12.6) = 12.6 \tag{F.31}$$

The condition given in Equation 7.28 is fulfilled.

$$L_{sp} = 12\,m \leq L = 12.6\,m \tag{F.32}$$

F.7 Corona Effect

The voltage gradient can be computed by using Equation 7.29.

$$E_c = m \cdot E_0 \cdot D_a \left(1 + \frac{C}{\sqrt{D_a \cdot r_{ext}}}\right) \cdot 100000 = 1600\,kV/m \tag{F.33}$$

The maximum voltage gradient at the surface of a three-phase conductor can be estimated using Equation 7.31.

$$E_m = \frac{h_e}{h_e - d_{ext}/2} \cdot E_a = \frac{1.46}{1.46 - 0.15/2} \cdot 310 \approx 310\,kV/m \tag{F.34}$$

$$h_e = \frac{h_{busbar} \cdot d_{busbar}}{\sqrt{4h_{busbar}^2 + d_{busbar}^2}} = \frac{6.5 \cdot 3}{\sqrt{46.5^2 + 3^2}} = 1.46\,m \tag{F.35}$$

$$E_a = \frac{1.1 \cdot U_{hg}}{\sqrt{3}} \cdot \frac{1}{\frac{d_{ext}}{2} \cdot ln\left(\frac{4\,h_e}{d_{ext}}\right)} = \frac{1.1 \cdot 132000}{\sqrt{3}} \cdot \frac{1}{\frac{0.15}{2} \cdot ln\left(\frac{4\,1.46}{0.15}\right)} = 310\,kV \tag{F.36}$$

The condition given in Equation 7.34 is fulfilled.

$$E_m = 310\,kV/m \leq E_c = 1600\,kV/m \tag{F.37}$$

F.8 Thermal Expansion

On one hand, the withstand short duration current density caused by the thermal equivalent short circuit current is obtained from Equation 7.35.

$$S_{th} = I_{th}/A_c = 40000/(3562 \cdot 10^{-6}) = 11.23 \cdot 10^6\,A/m^2 = 11.23\,A/mm^2 \tag{F.38}$$

On the other hand, the assigned withstand short duration current density is obtained from Equation 7.36.

$$S_{thr} = \sqrt{\frac{1}{T_{kr}} \cdot \frac{\kappa_{20} c \rho}{\alpha_{20}} \cdot \ln\left[\frac{1 + \alpha_{20}(\vartheta_e - 20)}{1 + \alpha_{20}(\vartheta_b - 20)}\right]} = 9.3 \cdot 10^7\,A/m^2 \tag{F.39}$$

The condition given in Equation 7.37 is fulfilled.

$$S_{th} = 11.23\,A/mm^2 \leq S_{thr}\sqrt{\frac{T_{kr}}{T_k}} = 93\,A/mm^2 \tag{F.40}$$

F.9 Selection of the busbar insulator

The post insulator that has been selected is c10-650. The condition given in Equation 7.38 is fulfilled. In addition, the maximum withstand voltage and the lightning impulse withstand voltage have to be higher than the system voltage and the lightning impulse of the system.

$$F_{\mathrm{T}} = 9974\,N \leq S_{\mathrm{Bending}} = 10000\,N \tag{F.41}$$