Overhead line Methodology

A methodology to design an overhead line

September 21, 2022

Soukayna Jermouni
Álvaro Benito Oliva
Ignacio Álvarez Iberlucea
Meyer Montagner Murcian [1]
Félix Pérez Cicala
Álvaro Pajares Barroso

RatedPower
Updating Engineering

[1]Provided essential software knowledge

Abstract

This methodology describes the design process to calculate an overhead line that connects the solar plant's station facility with the grid's point of interconnection. The objective of this document is to present the main steps followed to calculate the electrical and mechanical characteristics of an overhead line.

An overhead line design goes through several stages from planning to execution. This document will focus on explaining the stages that are in between. Following are the topics that will be covered in this document to explain the design of the overhead line:

- The line's blocks definition
- Selection of the line's phase conductor
- Insulation coordination and clearances
- Selection of the line's insulator
- Towers spotting
- Catenary and sags calculation
- Spans calculation
- Towers top-geometry calculation and selection of standard towers
- Earth wire calculation
- Electrical parameters calculation
- Tower forces calculation

Note: All the calculations that are presented in this document are carried out according to the IEC and EN standards.

Contents

List of Figures

List of Tables

Chapter 1

Overhead line criteria

In this chapter the overhead line's main elements and design criteria will be described.

1.1 Transmission and distribution criterion

The overhead line that is designed in this document can be of a transmission or of a distribution nature depending on the voltage and the type of the plant's interconnection facility. When a user selects a switching and breaking station, the voltage will be of a medium level as the station does not perform a voltage step-up function; hence, the power will be directly evacuated in a distribution line to the utility's distribution substation.

On the other hand, in the case of choosing a substation as the plant's interconnection facility, the station will have a high voltage at the receiving end which will define a transmission line to evacuate the generated capacity.

Furthermore, the minimum medium voltage considered is 5kV and the maximum is 45kV. Meanwhile, the high voltage level starts from 46kV up to 400kV.

1.2 Design criteria

In this methodology, several electrical requirements in designing an overhead line were considered, these considerations are defined to guarantee the stability and the capability of the line.

The overhead line is designed to connect the plant's interconnection facility at its voltage level; hence, the maximum high voltage accepted is 400kV as it is the highest acceptable voltage in the plant's substation.

Furthermore, to ensure the capability of the line, a maximum capacity that the line can evacuate is limited by both its voltage and length. Therefore, a thermal limit as well as a voltage drop and a power loss limit must be respected. In this regard, a voltage drop and a power loss of 5% [1] is considered as the maximum permissible.

On the other hand, the maximum voltage gradient on the conductor surface that is considered in selecting the conductor section is designed as 17kV/cm [1].

Regarding the reactive power, no way of compensation is considered in this methodology. The power factor at the receiving end is calculated accordingly and its calculation will be presented through this methodology.

1.3 Line feasibility criterion

The design of the line conforms to some criteria that define the possible voltages, capacities, and line lengths that comply with the voltage drop and power loss limits to perform efficiently. In this methodology, as mentioned in the previous section, a limit of 5% will be considered as the maximum permissible.

Based on several test cases that include different line lengths (short, medium, and long), different voltage levels from 5kV to 400kV, and different capacities, the resulting line feasibility is constrained to comply with the voltage drop and power loss limitation. This is also called electrical loadability of the line. In Figure 1.1 the maximum line lengths depending on the capacity and voltage that will guarantee the performance of the line are presented, these lengths are results of several tests as mentioned.

Upper Length Limit (km)		Voltage [V]									
		5000	11000	20000	32000	45000	66000	100000	132000	220000	400000
Capacity [MW]	0.05	300	200	200	150	150	150	100	100	50	50
	0.5	100	250	300	250	250	250	250	200	150	100
	1	50	200	300	300	250	250	250	250	200	100
	2	20	100	250	300	300	250	250	250	250	150
	5	10	50	150	250	300	300	250	250	250	250
	10	5	20	100	150	250	300	300	250	250	250
	20	2	10	50	100	150	250	300	300	300	300
	50	1	5	20	50	50	150	200	250	300	300
	100	0	2	10	20	50	100	150	200	300	300
	200	0	1	5	10	20	50	50	150	250	300
	500	0	0	2	5	10	20	50	50	150	250
	1000	0	0	1	2	5	10	20	20	100	200
	2000	0	0	0	1	2	5	10	20	50	150
	3000	0	0	0	0	1	2	5	10	20	100
	4000	0	0	0	0	1	2	5	10	20	50

Figure 1.1: The loadability factor

1.4 Terrain data

The elevation data under the overhead line is calculated to perform the spotting of the towers within the line. An inverse distance weighted (IDW) interpolation of the elevation data is applied when necessary and it considers the coverage of the digital elevation model. Wherever there is a gap in the elevation, the interpolator will fill the gap accordingly. The algorithm used by the interpolator is explained thoroughly in [2].

1.5 Block definition

The overhead line is defined as blocks of towers that are grouped based on the deflection of the path, an illustration of blocks and deflections are shown in Figure 1.2 Consequently, the first and last towers of each block are tension towers. Moreover, every two adjacent blocks will share one tower.

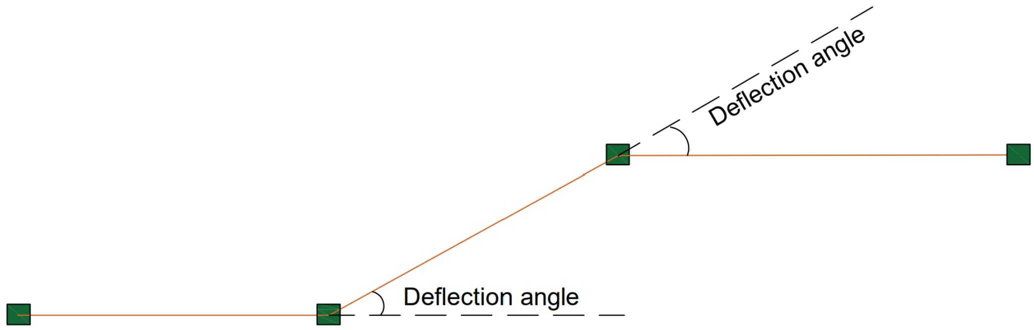

Figure 1.2: Blocks definition

1.5.1 Deflection angle

The deflection angle is the angle by which the line deviates and by which a block is defined. For a new block to be considered in the line, the deflection angle should be higher than 2° or lower than -2°. To calculate the deflection angle a simple geometric function is used to get the angle between the three towers, and from it we deduce the deflection angle of the line.

1.5.2 Spans

The line's blocks are themselves characterized by the different spans that are used further in mechanical calculations. In this section, the types of the spans considered in the calculation are depicted.

Length span

The length span is the distance between two adjacent towers taking into account the elevation difference between the two towers.

Weight span

The weight span is the distance between the lowest points of the sags in two adjacent spans. The lowest points are calculated from the catenary of the line. Moreover, the weight span represents the vertical load applied to the tower due to the weight of the conductor.

Wind span

The wind span is defined as half of the sum of two adjacent spans in a profile view. The wind span represents the horizontal load applied on the tower due to the wind blowing on the conductor.

In Figure 1.3 the different spans of the line are illustrated.

Ruling span

On the other hand, the ruling span is considered as a mean span within a block. Each block has its ruling span that is used to approximately represent its mechanical characteristics. The

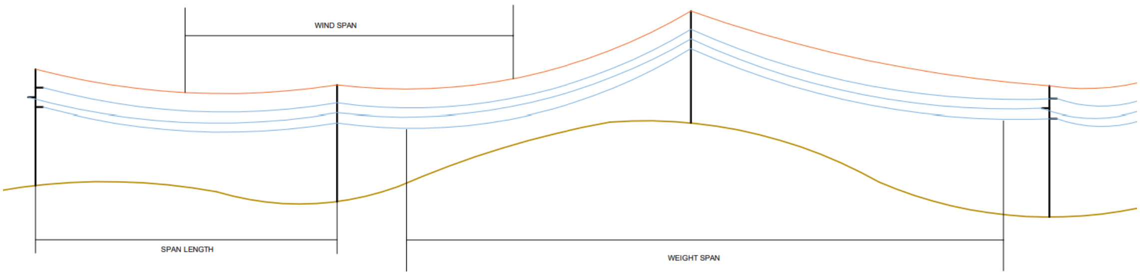

Figure 1.3: Spans of the line

theoretical ruling span is calculated to simplify the sagging calculation of the conductors, and it is calculated using Equation (1.1) by making the assumption that the towers are of equal elevations and that the horizontal tension is constant throughout the block.

$$S_r = \sqrt{\frac{\Sigma S^3}{\Sigma S}} \tag{1.1}$$

Where:

- S_r is the theoretical ruling span [m]
- S is a span length [m]

1.6 Type of towers

The towers of an overhead line can be of different types depending on the function of the line, the number of circuits, the utility's constraints as well as the country's requirements. They determine an important part of the line's investment as well as the reliability of the line.

The towers that are used throughout this methodology are lattice steel towers of three types:

- Suspension tower: It carries the conductor when the line is straight, the longer the blocks with suspension towers the better the investment of the line would be.
- Angle tower: It carries the conductor where the line deflects and changes direction. Unlike the suspension towers, they support more tensile forces from the conductors.
- Dead-end towers: They are the towers at both ends of the line, they are usually connected to the substation's portals that generally leads to higher load at both ends.

1.7 Type of insulators

The insulators are another important component in the overhead line, they are installed to connect the live conductors with the earthed towers. Their type is defined based on the type of the tower they are connected to. In this methodology two types of insulators are considered:

- Suspension insulator: It is the insulator connecting the conductor to the suspension tower when the line is straight.
- Tension insulator: It is the insulator that attaches the conductors to angle or dead-end towers, it always follows the straining of the conductor.

Chapter 2

Phase conductor

The overhead line conductors correspond to up to 50% of the total investment of the line [3]; hence, the importance of the selection criteria of the conductor's section and its bundles. In this chapter, the type of the phase conductors that are considered will be described, the selection consideration will be depicted, and the bundle calculation will be presented.

2.1 Conductor's type

The overhead line conductors are usually bare conductors not insulated and stranded that can be made of one material or a composition of different materials.

The conductors that were chosen in this methodology are of two types, conductors that are used for medium voltage lines and made of Aluminum and conductors that are used in high voltage lines which are made of a composition of Aluminum and steel. Both types of conductors are designed following the IEC standard 61089 [3].

2.1.1 Medium voltage conductors

For the distribution lines, AAAC conductors are used which are made solely of Aluminum alloy and are characterized by their lighter weights and lower electrical losses. The designation of an AAAC conductors according to IEC [3] is identified by a number that corresponds to the section of the conductor and a code that refers to the material used.

From the standardized conductors, several parameters are extracted such as the cross-section, the number of stranding, the nominal diameter, the weight, and the rated strength of the conductor.

Moreover, other parameters are considered based on [3] to calculate the resistance of the conductor as well as its mechanical characteristics; these parameters are:

The resistivity of an Aluminum conductor of type A and B being: $\rho = 3.27 \cdot 10^{-8} \Omega m$

The coefficient of linear thermal expansion of an Aluminum alloy conductor being $\alpha = 23 \cdot 10^{-6 \circ} C^{-1}$

And the elasticity of the Aluminum alloy conductor being $E = 55.6 \cdot 10^{9} Pa$

2.1.2 High voltage conductors

As for the transmission line, the ACSR conductors are chosen for the high voltage. The ACSR conductors are bare and made of layers of Aluminum wires on a galvanized steel wires on the core. This conductor is characterized by a high tensile strength and suitability in large spans. The ACSR conductors used in this methodology are all designed according to IEC [3].

This latter's designation is defined with a number that corresponds to the cross-section of the conductor and two codes that represent the composition materials. Using the standardized conductors, some mechanical parameters are extracted such as the section, the number of stranding, the nominal diameter, the unitary weight, and the rated strength of the conductor.

These previous parameters along with others that are specific to ACSR conductors are used to select the right conductor of the line and to calculate further mechanical characteristics. The specific parameters are:

The elasticity of the Aluminum steel reinforced of the conductor being $E = 190 \cdot 10^9 Pa$

The coefficient of linear thermal expansion of an Aluminum steel reinforced conductor being $\alpha = 11.5 \cdot 10^{-6} {}^{\circ}C^{-1}$

2.2 Selection criteria

The selection of a distribution or a transmission conductor relies mainly on the current loading; generally, the operating current leads the conductor to run at a higher temperature, nevertheless, the conductor's temperature should not exceed an admissible limit in order to maintain its mechanical strength.

Therefore, two main criteria are investigated, an electrical criterion to check the thermal limit of the conductor and a mechanical criterion that guarantee the strength withstand of this latter.

In addition, in this methodology, the conductors undergo a selection based on the voltage gradient, the voltage drop and the power loss limits. The compliant conductor, therefore, must withstand the thermal unit, comply with the voltage gradient and voltage drop maximum limits, and must withstand the corresponding tensile strength in the line.

2.2.1 Maximum admissible current

For an overhead line to be reliable, it must be able to withstand the electrical load defined by the operating current. Hence, the conductor's cross-section design must conform with the maximum admissible current of the line.

For given ambient conditions, the maximum admissible current is calculated based on the conductor's predetermined temperature and its DC resistance at maximum temperature [4]. To calculate the DC resistance of the conductor at maximum temperature Equation (2.1) is used:

$$R_T = R_{T_f}\left[1 + \alpha(T_{max} - 20)\right] \tag{2.1}$$

Where:

- R_T is the electrical resistance of the conductor per unit length at maximum temperature T $[\Omega/m]$
- R_{T_f} is the DC resistance per unit length at a reference temperature being $20°C$ $[\Omega/m]$
- α is the variation of the resistance with temperature being $4.03 \cdot 10^{-3}$ $[1/°C]$
- T_{max} is the maximum temperature being 80 $[°C]$

$$R_{T_f} = \frac{\rho}{s} \tag{2.2}$$

Where:

- R_{T_f} is the electrical resistance of the conductor per unit length at reference temperature T being $20°C$ $[\Omega/m]$
- ρ is the resistivity of the conductor $[\Omega \cdot m]$
- s is the cross-section of the conductor $[m^2]$

To calculate the maximum admissible current a heat balance at the conductor should be reached; this heat balance is determined based on the solar heat gained by the conductor surface, the heat loss by convection, and the heat loss caused by radiation of the conductor.

Using the unit length DC resistance at maximum temperature of the conducto;, the heat balanced is reflected in Equation (2.3):

$$I_{max} = \sqrt{\frac{N_R + N_C - N_S}{R_T}} \tag{2.3}$$

Where:

- I_{max} is the maximum admissible current for one conductor $[A]$
- N_R is the heat loss by radiation of the conductor $[W/m]$
- N_C is the heat loss by convection $[W/m]$
- N_S is the solar heat gain by the conductor's surface $[W/m]$
- R_T is the electrical resistance of the conductor per unit length at reference temperature T being $20°C$ $[\Omega/m]$

- Heat loss by radiation:

Given the nominal diameter of the conductor, the heat loss by radiation is given by the following equation:

$$N_R = k \cdot \pi \cdot d \cdot K_e({T_{max}}^4 - {T_{am}}^4) \tag{2.4}$$

Where:

- N_R is the heat loss by radiation of the conductor $[W/m]$
- k is the Stefan-Boltzmann constant being $5.67 \cdot 10^{-8}$ $[Wm^{-2}K^{-4}]$

- d is the nominal diameter of the conductor $[m]$
- K_e is the emissivity coefficient with respect to a black body
- T_{max} is the maximum temperature being 353 $[K]$
- T_{am} is the ambient temperature being 318 $[K]$

- Heat loss by convection:

The heat loss by convection of the conductor is calculated as the following:

$$N_C = \lambda \cdot Nu \cdot \pi \cdot (T_{max} - T_{am}) \tag{2.5}$$

Where:

- N_C is the heat loss by convection $[W/m]$
- λ is the thermal conductivity of the air in contact with the conductor $[W/(K \cdot m)]$
- Nu is the Nusselt number calculated in Equation (2.6)
- T_{max} is the maximum temperature being 353 $[K]$
- T_{am} is the ambient temperature being 318 $[K]$

The Nusselt number is calculated as:

$$Nu = 0.65 \cdot {R_e}^{0.2} + 0.23 \cdot {R_e}^{0.61} \tag{2.6}$$

Where:

- Nu is the Nusselt number
- R_e is the Reynolds number calculated in [eq]

The Reynolds number is calculated following the equation:

$$R_e = 1.644 \cdot 10^9 \cdot d \cdot v \cdot [T_{am} + 0.5 \cdot (T_{max} - T_{am})]^{-1.78} \tag{2.7}$$

Where:

- R_e is the Reynolds number
- d is the the nominal diameter of the conductor $[m]$
- v is the wind speed being 2.016 (0.5 m/s) $[km/h]$
- T_{max} is the maximum temperature being 353 $[K]$
- T_{am} is the ambient temperature being 318 $[K]$

- Solar heat gain:

The solar heat gain by the conductor's surface is calculated by the following equation:

$$N_S = Y \cdot d \cdot S_i \tag{2.8}$$

Where:

- N_S is the solar heat gain by the conductor's surface $[W/m]$
- Y is the solar radiation absorption coefficient being 0.8
- d is the nominal diameter of the conductor $[m]$
- S_i is the intensity of solar radiation being 1045 $[W/m^2]$

2.2.2 Minimum tensile strength

After selecting the conductors that withstand electrically, the mechanical criterion should be considered to guarantee a compliant conductor. Depending on the voltage of the line, a target span is defined as seen in Table 2.1; if this latter is between a certain range, a corresponding minimum tensile strength is selected for the compliant conductor to withstand as seen in Table 2.2.

Table 2.1: The target allowable span lengths [Source: own elaboration]

Rated voltage U [kV]	Target span [m]
⩽24	100
⩽132	200
⩽220	250
⩽400	300
>400	400

The minimum tensile strength values depending on the target spans were obtained with an empirical approach which consisted in analyzing different lines with different conductors under several voltage levels. As the tensile strength is directly related to the catenary of the conductor, it is concluded that the weaker conductors will result in higher catenaries and to avoid not respecting the target span lengths, a minimum tensile strength limit is defined based on the allowable span length as seen in Table 2.2.

Table 2.2: The minimum tensile strength [Source: own elaboration]

Target span [m]	Minimum Tensile Strength [N]
⩽100	20000
⩽200	45000
⩽250	60000
⩽300	75000
>300	90000

2.2.3 Voltage gradient

The voltage gradient or the critical surface gradient is the electrical potential across the conductor surface. When the electrical field reaches the critical surface gradient, Corona effect occurs which causes extra losses. Hence, the voltage gradient should be considered when selecting the cross-section of a conductor and should be limited; consequently, in this methodology the voltage gradient is limited to 17kV/cm [5].

The voltage gradient of a conductor is calculated using the following Equation (A.7)

$$E_i = \frac{C_i}{2\pi\epsilon_0 \cdot n_2 \cdot r}[1 + 2 \cdot (r/s)(n_2 - 1) \cdot sin(\pi/n_2)]\frac{U}{\sqrt{3} \cdot 100} \tag{2.9}$$

Where:

- E_i is the voltage gradient $[kV/cm]$
- C_i is the capacitance per unit length of a conductor, the capacitance is calculated using Equation (9.36) or Equation (9.35) $[F/m]$
- ϵ_0 is the dielectric constant being $8.854 \cdot 10^{-12}$ $[F/m]$
- n_2 is the number of conductors per bundle
- r is the radius of the sub-conductor $[m]$
- s is the distance between the sub-conductors being 400 $[mm]$
- U is the rated voltage $[kV]$

In addition to the voltage gradient limit, the selected cross-section conductor must comply with the voltage drop and losses limit which are considered as 5% based on [3].

2.3 Bundle calculation

The number of sub-conductors per phase are calculated based on the voltage and capacity of the overhead line. Considering different possible arrangements depending on the voltage level, the number of conductors per bundle is selected based on the capacity of the corresponding arrangement.

Furthermore, in the case of not finding a compliant conductor per phase according to the voltage gradient limit, the number of sub-conductors per bundle is increased till a convenient cross-section is selected.

Table 2.3: Number of sub-conductors calculation [Source: Own elaboration]

Rated voltage U [kV]	Capacity S [MVA]	Bundle number
⩽15	⩽10	1
	⩽20	2
	>20	4
⩽30	⩽50	1
	⩽100	2
	>100	4
⩽66	⩽160	1
	⩽320	2
	>320	4
⩽132	⩽160	1
	⩽640	2
	>640	4
⩽220	⩽340	1
	⩽1360	2
	>1360	4
<400	⩽2000	2
	⩽2500	3
	>2500	4

Chapter 3

Earth Wire

Lightning strike is one of the main reasons behind the sudden outages of an overhead line, and the earth wire comes as a protection schema to reduce these unexpected outages.

Therefore, the earth wire's main function is to not only to protect the phase conductors from possible lightning but also to return the phase-to-earth short-circuit current. Consequently, they should be designed and specified adequately to serve their function.

In addition, an earth wire is installed with a shield angle that is defined between 10° and 35°; in this methodology, the earth wires are designed with a shield angle of 30°.

3.1 Earth wire type

The earth wires can be of steel combined with low aluminum material to take advantage of their high level of conductivity. However, recently the use of an optical ground wire has become more relevant.

The earth wires chosen in this methodology are of optical fiber wire type (OPGW) to extend their purposes and be used to carry telecommunication signals as well. The said earth wires are obtained from [6] and designed according to IEC 60794-4 and IEC 61395.

The selected four OPGW wires are listed in table 3.1

Table 3.1: The OPGW wire. Source ZTT catalog [6]

Code OPGW	Diameter [mm]	Number of fibers	Weight [kg/m]	Maximum load [N]	Section [mm²]	Short-circuit capacity $[kA^2 \cdot s]$	Resistance $[\Omega/m]$
1C 1/36B1	10.2	36	0.394	67800.0	0.000054	13.9	1.58
L-48B1-85	12.30	48	0.540	85600.0	0.000085	43.5	0.75
YS-2C 1/48B1	15.25	48	0.716	93800.0	0.000133	138.1	0.33
2S 1/48B1	17.2	48	0.796	106300.0	0.000165	213.7	0.270

3.2 Earth wire selection

The earth wires chosen in this methodology are of different sizes, to select the adequate size for a certain line, an electrical criteria based on the short-circuit current is considered.

Based on the line's maximum voltage, the design short-circuit current is calculated according to the IEC standard [7], [8], [9], and [10] moreover, the short-circuit time is taken as 0.3s. Hence, the short-circuit design capacity is calculated using Equation (3.1) and compared to the earth wire's short-circuit capacity. The earth wire that withstands the said capacity is selected.

$$S_{sc} = (I_{sc}/1000)^2 \cdot T_k \tag{3.1}$$

Where:

- S_{sc} is the short-circuit capacity $[kA^2 \cdot s]$
- I_{sc} is the design short-circuit current $[kA]$
- T_k is the short-circuit duration set as 0.3 $[s]$

Chapter 4

Tower Selection

The overhead line towers are another important component in granting the right-of-way as well as in the investment of the power line, depending on their design and material, the cost of the line can change remarkably. Therefore, the towers not only define the aesthetic of the line but also determine its reliability by withstanding the conductor's forces and loads.

In this chapter the overhead line's towers will be described, their types upon voltage level and number of circuit selection criteria will be presented.

4.1 Towers types

The overhead line towers shape differ from country to country and from a utility operator to another. However, in this methodology, there are six different tower shapes designed for both medium and high voltages, for simple and double circuits, and with one earth wire or two earth wires. Furthermore, the towers material that is used in this methodology is of lattice steel for all voltage levels.

4.1.1 Medium voltage towers

The chosen towers to be used for the MV lines are of two different shapes:

- **Single fork tower:** is a tower with one circuit (Simplex) and one earth wire arrangement and it has the shape of a fork with its three crossarms being in one side.
- **MV Double fork tower:** is a tower with two circuits (Duplex) and two earth wires arrangement and it has the shape of two forks with one circuit crossarms being in one side and the other circuit in the opposite side.

The two MV towers are illustrated in Figure 4.1 following the order listed above.

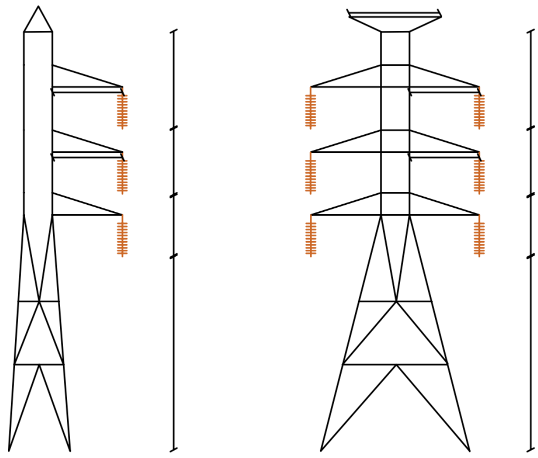

Figure 4.1: MV line towers shape: (a)Single fork tower | (b)MV Double fork tower

4.1.2 High voltage towers

On the other hand, the four high voltage line towers are designed as follows:

- **S shape tower:** is a tower with one circuit (Simplex) one earth wire arrangement and it has a shape of an S letter with 2 cross arms in one side and the third in the opposite side.
- **Single Pi tower:** is a tower with one circuit (Simplex) and two earth wires arrangement; it has the shape of the Greek letter Pi with the three phases aligned horizontally.
- **Double T tower:** is a tower with two circuits (Duplex) and two earth wires arrangement and it has the shape of the letter T with two levels, one circuit cross-arms being in one side and the other circuit in the opposite side.
- **HV Double fork tower:** similar to the MV double fork tower, it is a tower with two circuits (Duplex) and two earth wires arrangement and it has the shape of two forks with one circuit cross-arms being in one side and the other circuit in the opposite side. The difference with its MV similar is the middle cross-arms being longer than the others.

The HV towers shape are shown in the Figure 4.2 following the order listed above.

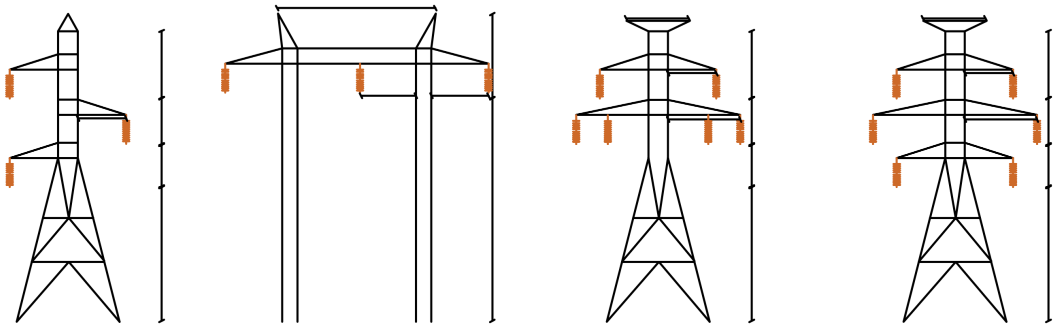

Figure 4.2: HV line towers shape: (a) Single S tower | (b) Single Pi tower | (c) Double T tower | (d) HV Double fork tower

4.2 Towers selection criteria

Several aspects are considered in selecting a tower design, such as its impact in land use, the ability to evacuate the necessary power, or the visual impact it will have on the landscape.

To select the right tower in this methodology, a voltage and circuit arrangement criteria were considered. For each voltage level, MV or HV, depending on the number of circuits as well as the voltage itself, a tower type is selected. The different voltage levels considered in the towers selection is presented in Table 4.1.

Table 4.1: Tower types selection

Voltage level	Circuit arrangement	Voltage level [kV]	Tower type
MV	Simplex	–	Single fork tower
	Duplex	–	MV Double fork tower
HV	Simplex	⩽245	Single S tower
	Simplex	>245	Single Pi tower
	Duplex	⩽245	HV double fork tower
	Duplex	>245	Double T tower

4.3 Circuit selection

The tower's type selection is based on the number of circuits, that in its turn depends on the voltage and capacity evacuated in the line. For a certain level of voltage, the circuit arrangements is chosen to be simplex or duplex upon how much capacity is transmitted. In the Table 4.2 , the possible arrangement used in the number of circuit selection, hence, the tower type, are presented.

Table 4.2: Number of circuits calculation. [Source: Own elaboration]

Rated voltage U [kV]	Capacity S [MVA]	Number of circuits
⩽15	⩽4	1
	>4	2
⩽30	⩽20	1
	>20	2
⩽66	⩽80	1
	>80	2
⩽132	⩽320	1
	>320	2
⩽220	⩽680	1
	>680	2
⩽400	⩽1400	1
	>1400	2

Chapter 5

Insulation coordination

As mentioned in a previous chapter, the reliability of an overhead line is impacted by the electrical and mechanical performance of the line. Consequently, tower electrical clearances play an important role to reach a good mechanical performance. More particularly, the design of the insulation coordination under, not only, temporary stresses but also different over-voltages is crucial in defining the electrical clearances.

In this chapter, the insulation coordination design of the overhead line is described in obedience with the IEC standard [11]. The selection of the insulation levels will be explained and the calculation of the withstand voltage to ensure the insulation of the system is stated.

5.1 General procedure

The insulation coordination procedure has an aim to guarantee a low probability of line damage caused by over-voltages and it consists of treating several parameters to reach its objective.

The voltages are classified into two classes based on the IEC standard [11], and for each class only some of the over-voltages are considered to calculate the withstand voltage. For class I voltages (From 1kV to 245kV) both the temporary and the fast-front over-voltages are considered. On the other hand, for class II voltages (Starting from 245kV) the fast-front and slow-front over-voltages are considered in the calculation.

A detailed review of the procedure is shown in the substation methodology [12] chapter 4 where the procedure details for class I and II are presented according to the IEC standard.

However, the insulation coordination procedure of an overhead line has few considerations that are different from the procedure followed for the substation. To calculate the power frequency over-voltage, the discharge factor of the earth fault for the overhead line calculation is considered as 1.3 instead of 1.4 for the substation. Moreover, the defect factor is also considered as 1.3 for the overhead line.

In addition to that, another difference in determining the withstand voltage for the overhead line is the termination of the procedure followed in the substation when finding the required withstand voltage [11].

Finally, normalized voltage levels are not considered in this calculation.

5.2 Determination of withstand voltage

Calculating the required withstand voltage follows the same steps found in the substation methodology [12]. The power-frequency, slow-front and the fast-front over-voltages are calculated based on the maximum voltage of the system by calculating both phase-phase and phase-earth over-voltages considering the altitude of the project.

Furthermore, the statistical slow-front voltage is calculated to determine the clearances; it is calculated based on the primary slow front over-voltage as follows:

$$E_2 = \frac{U_{et} + 0.25}{1.25} \cdot U \cdot \sqrt{2/3} \tag{5.1}$$

Where:

- E_2 is the statistical switching over-voltage $[p.u]$
- U_{et} is the truncation value of the cumulative distribution of the phase-to-earth over-voltages in p.u
- U is the maximum voltage of the system $[kV]$

Chapter 6

Insulators

The insulator plays important electrical and mechanical roles in the overhead line design, it is, therefore, necessary to design it considering the insulation performance and the mechanical withstand.

In this chapter the insulator's types upon voltage level are described and the criteria used to select the adequate insulator is presented.

6.1 Insulator's types

The insulators of an overhead line come in different types and shapes with different materials; in this methodology, the insulators are designed according to the IEC standard [13]. Namely, long-rod and cap and pin insulators made of polymer and glass respectively are used to select the correct suspension and tension insulators of the line.

6.1.1 Medium voltage insulator

For the medium voltage lines, the long-rod insulators are chosen for both suspension and angle towers. The long-rod insulators are characterized by their high reliability especially under high pollution conditions. This type of insulator comes with two different caps, in this methodology only the clevis and tongue cap type is considered.

In the following Table 6.1, the insulators used in this methodology are listed with their corresponding lightning impulse, minimum failing load, diameter and maximum length.

Table 6.1: Long-rod insulators according to IEC. Source IEC 60433 [14] and [15]

Designation	lightning impulse [V]	Failing load [N]	Diameter [m]	Maximum length [m]	Minimum creepage [m]
L40 C170	170000	40000	0.16	0.4	0.576
L60 C170	170000	60000	0.16	0.42	0.576
L100 C170	170000	100000	0.18	0.475	0.576
L100 C250	250000	100000	0.18	0.6	0.832
L100 C325	325000	100000	0.18	0.9	1.16
L100 C450	450000	100000	0.18	1.12	1.968
L100 C550	550000	100000	0.18	1.27	1.968
L120 C325	325000	120000	0.2	0.905	1.16
L120 C450	450000	120000	0.2	1.12	1.968
L120 C550	550000	120000	0.2	1.275	1.968
L120 C650	650000	120000	0.2	1.465	2.32
L160 C325	325000	160000	0.21	0.92	1.16
L160 C450	450000	160000	0.21	1.135	1.968
L160 C550	550000	160000	0.21	1.29	1.968
L160 C650	650000	160000	0.21	1.465	2.32
L210 C325	325000	210000	0.22	0.94	1.16
L210 C450	450000	210000	0.22	1.155	1.968
L210 C550	550000	210000	0.22	1.31	1.968
L210 C650	650000	210000	0.22	1.5	2.32
L250 C550	550000	250000	0.23	1.335	1.968
L250 C650	650000	250000	0.23	1.53	2.32
L300 C550	550000	300000	0.24	1.365	1.968
L300 C650	650000	300000	0.24	1.56	2.320
L330 C550	550000	330000	0.25	1.4	1.968
L330 C650	650000	360000	0.24	1.595	2.32
L360 C550	550000	360000	0.25	1.41	1.968
L360 C650	650000	360000	0.25	1.6	2.32
L400 C550	550000	400000	0.26	1.46	1.968
L400 C650	650000	400000	0.26	1.66	2.32
L420 C550	550000	420000	0.26	1.46	1.968
L420 C650	650000	420000	0.26	1.66	2.32
L530 C550	550000	530000	0.27	1.52	1.968
L530 C650	650000	530000	0.27	1.72	2.32
L550 C550	550000	550000	0.27	1.52	1.968
L550 C650	650000	550000	0.27	1.72	2.32
CSC-750/2720	750000	210000	0.2	1.395	2.72
CSC-950/3920	950000	210000	0.25	1.775	3.92
CSC-1050/3920	1050000	210000	0.2	1.97	3.92

6.1.2 High voltage insulator

On the other hand, the cap-and-pin insulators were chosen to select the appropriate insulators for the high voltage level. The cap-and-pin insulator is known for its high mechanical strength and characterized by larger creepage distance. In Table 6.2 the cap-and-pin insulators used in this methodology are listed.

Table 6.2: Cap-and-pin insulators according to IEC. Source: [13] and [15]

Designation	lightning impulse [V]	Failing load [N]	Diameter [m]	Maximum length [m]	Weight [kg]	Minimum creepage [m]
U40B	70000	40000	0.11	0.175	1.6	0.19
U70BS	100000	70000	0.127	0.255	3.6	0.295
U70BL	100000	70000	0.146	0.255	3.6	0.295
U100BS	100000	100000	0.127	0.255	3.9	0.295
U100BL	100000	100000	0.146	0.255	4	0.295
U120B	100000	120000	0.146	0.255	3.9	0.295
U160BS	110000	160000	0.146	0.28	6.2	0.315
U160BL	110000	160000	0.17	0.28	6.2	0.34
U210B	110000	210000	0.17	0.3	7.2	0.37
U300B	130000	300000	0.195	0.33	10	0.39

6.2 Selection criteria

The selection of the appropriate insulators for suspension and angle towers requires two main criterion, one electrical and another mechanical. Both criteria should be respected for the MV and HV voltage levels.

6.2.1 Electrical criterion

For the electrical criterion, the selected insulator should withstand the electrical requirements for a certain valid length of the string. For both types of insulators, the necessary number of elements to form an insulator string is calculated such that the total elements withstand the maximum voltage under normal conditions, under wet conditions, and under lightning impulse. The calculation of the number of elements for each condition is presented using Equations (6.1), (6.2) and (6.3).

Number of elements under normal conditions:

$$n_{normal} \geqslant \frac{U_s \cdot \epsilon_0}{\epsilon} \tag{6.1}$$

Where:

- n_{normal} is the number of elements necessary to withstand maximum voltage under normal conditions
- U_s is the maximum voltage of the system $[V]$
- ϵ_0 is the minimum nominal creepage for a medium level of polution being $20 \cdot 10^{-6}$ according to IEC [11] and [16] $[m/V]$
- ϵ is the insulator creepage distance $[m]$

Number of elements under wet conditions:

$$n_{wet} \geqslant \frac{U_{pf}}{U_w} \tag{6.2}$$

Where:

- n_{wet} is the number of elements necessary to withstand maximum voltage under wet conditions
- U_{pf} is the maximum power frequency voltage $[V]$
- U_w is the long term wet voltage of the insulator $[V]$

Number of elements under lightning impulse:

$$n_{impulse} \geqslant \frac{U_{ff}}{U_l} \tag{6.3}$$

Where:

- $n_{impulse}$ is the number of elements necessary to withstand maximum voltage under lightning impulse
- U_{ff} is the maximum lightning withstand voltage $[V]$
- U_l is the maximum lightning voltage of the insulator $[V]$

The number of elements composing the insulator string is the biggest number of elements among the three conditions calculated above. On the other hand, the insulator string must comply with the minimum clearance phase to earth to guarantee the clearances respect for all parts of the tower. To validate the insulator length a safety factor is applied to the minimum phase-earth clearance to consider possible swing angle, then the length of the insulator is calculated using Equation (6.4).

$$L_{ins} = n_{ele} \cdot l_{ele} \tag{6.4}$$

Where:

- L_{ins} is the length of the insulator $[m]$
- n_{ele} is the total number of elements composing the insulator string
- l_{ele} is the length of the insulator's element $[m]$

The insulator length calculated above, should be higher than the minimum length defined by the phase to earth clearance such as: $d_{el} \cdot 1.1$ for the insulator to be electrically valid. Once the electrical insulator is selected, the insulator parameters such as the length, weight or minimum creepage are calculated upon the number of its elements.

6.2.2 Mechanical criterion

Mechanically, the insulator must withstand the maximum load of the conductors to have the optimal choice of insulator sets; based on this criterion, different combinations of insulators per conductor bundle are tested. For every combination, the insulator strength against the conductor's bundle is checked; if the insulator withstands the bundle's load, the number of insulators set is kept. If it doesn't withstand the load, a new configuration with more insulators is tried. The possible sets are simplex with one insulator, duplex with two, or quadruplex with four insulators per conductor(s).

From the possible insulator combinations, the insulator with the closest minimum failing load to the expected tensile strength is selected, this latter is the typical tensile strength of insulators depending on the voltage. In Table 6.3 the expected tensile strength is chosen based on several study cases from Spain.

Table 6.3: The expected tensile strength for insulators

Maximum voltage U [kV]	Expected tensile strength [N]
$\leqslant$36	70000
$\leqslant$72.5	120000
$\leqslant$245	160000
$>$ 245	210000

Ultimately, the insulators that have a minimum failing load closest one to the expected tensile strength are the candidates that respect both the electrical and mechanical criteria. However, there is a possibility to get two insulators with same tensile strength, and to select the appropriate one, the insulator with the least length and creepage distance is prioritized by giving more importance to minimizing the length.

Chapter 7

Clearances

There are several types of electrical clearances, some are determined to prevent disruptive discharges between the conductor and the earthed tower, others to prevent disruptive discharges between phase conductors. In addition, there are mid-span clearances that need to be respected during wind conditions and other safety clearances to obstacles or possible objects in the path.

In this chapter the electrical clearances covered in this methodology will be described.

7.1 Electrical clearances

The electrical clearances are necessary to design the top-geometry of the towers to ensure the line's reliability. These internal phase to phase and phase to earth clearances are calculated based on the required withstand voltage and the statistical switching over-voltage, both calculated from the insulation coordination procedure. Chapter 5

For each over-voltage stress, the required withstand voltage is calculated and used to determine the required electrical clearances phase-phase and phase-earth. Following, the clearances formulas are presented for each voltage stress.

After the calculation of phase to phase and phase to earth clearances for each over-voltage, the maximum clearances among them are chosen and compared against standard clearances according to EN 50341 [17]. Based on the voltage of the system, as listed in the Table 7.1, standard phase to phase and phase to earth clearances are selected. The maximum between the clearances calculated and the standard values are the final minimum clearances to be respected when designing the towers.

Table 7.1: The minimum standard clearances pp and pe. Source: EN standard [17]

Maximum voltage U [kV]	Phase-earth clearance [m]	Phase-phase clearance [m]
3.6	0.08	0.1
7.2	0.09	0.1
12	0.12	0.15
17.5	0.16	0.2
24	0.22	0.25
30	0.27	0.33
36	0.35	0.4
52	0.6	0.7
72.5	0.7	0.8
82.5	0.75	0.85
100	0.9	1.05
123	1.0	1.15
145	1.2	1.4
170	1.3	1.5
245	1.7	2.0
300	2.1	2.4
420	2.8	3.2
525	3.5	4.0
765	4.9	5.6

7.1.1 Phase to phase clearances

The phase-phase clearance is the minimum distance that must be respected between the phase conductors and it is calculated for each stress as follows:

Fast-front overvoltages

$$D_{pp-ff} = \frac{1.2 \cdot U_{90\% ff-ins}}{530 \cdot K_a \cdot K_{z-ff} \cdot K_{g-ff}} \tag{7.1}$$

Where:

- D_{pp-ff} is the phase to phase clearance with fast-front overvoltages $[m]$
- $U_{90\% ff-ins}$ is the lightning withstand voltage of the insulator $[kV]$
- K_a is the altitude factor calculated using table 2.15 found in [3]
- K_{z-ff} is the deviation factor for fast-front overvoltages being 0.961 according to [3]
- K_{g-ff} is the gap factor for fast-front overvoltages being 1.16 according to [3]

Slow-front overvoltages

$$D_{pp-sf} = 2.17 \cdot \left[\frac{1.4 \cdot K_{cs} \cdot U_{2\% sf}}{1080 \cdot K_a \cdot K_{z-sf} \cdot K_{g-sf}} - 1 \right] \tag{7.2}$$

Where:

- D_{pp-sf} is the phase to phase clearance with slow-front overvoltages $[m]$
- K_{cs} is the statistical coordination factor being 1.05 [3]
- $U_{2\%sf}$ is the statistical switching overvoltage $[kV]$
- K_a is the altitude factor using table 2.15 found in [3]
- K_{z-sf} is the deviation factor for slow-front overvoltages being 0.922 according to [3]
- K_{g-sf} is the gap factor for slow-front overvoltages being 1.6 according to [3]

Power frequency voltages

$$D_{pp-pf} = 1.64 \cdot \left[exp \frac{U}{750 \cdot K_a \cdot K_{z-pf} \cdot K_{g-pf}} - 1 \right]^{0.833} \tag{7.3}$$

Where:

- D_{pp-pf} is the phase to phase clearance with power frequency voltages $[m]$
- U is the maximum voltage of the system $[kV]$
- K_a is the altitude factor
- K_{z-pf} is the deviation factor for power frequency voltages being 0.910 according to [3]
- K_{g-pf} is the gap factor for power frequency voltages being 1.26 according to [3]

7.1.2 Phase to earth clearances

The phase to earth clearance is the minimum distance to be respected between a phase conductor and both an earthed part of the tower and the earth wire, and it is calculated for each stress voltage as follows:

Fast-front overvoltages

$$D_{pe-ff} = \frac{U_{90\%ff-ins}}{530 \cdot K_a \cdot K_{z-ff} \cdot K_{g-ff}} \tag{7.4}$$

Where:

- D_{pe-ff} is the phase to earth clearance with fast-front overvoltages $[m]$
- $U_{90\%ff-ins}$ is the lightning withstand voltage of the insulator $[kV]$
- K_a is the altitude factor
- K_{z-ff} is the deviation factor for fast-front overvoltages being 0.961 according to [3]
- K_{g-ff} is the gap factor for fast-front overvoltages being 1.12 according to [3]

Slow-front overvoltages

$$D_{pe-sf} = 2.17 \cdot \left[exp \frac{K_{cs} \cdot U_{2\%sf}}{1080 \cdot K_a \cdot K_{z-sf} \cdot K_{g-sf}} - 1 \right] \tag{7.5}$$

Where:

- D_{pe-sf} is the phase to earth clearance with slow-front overvoltages $[m]$
- K_{cs} is the statistical coordination factor being 1.05 [3]
- $U_{2\%sf}$ is the statistical switching overvoltage $[kV]$
- K_a is the altitude factor
- K_{z-sf} is the deviation factor for slow-front overvoltages being 0.922 according to [3]
- K_{g-sf} is the gap factor for slow-front overvoltages being 1.45 according to [3]

Power frequency voltages

$$D_{pe-pf} = 1.64 \cdot \left[exp \frac{U}{750 \cdot \sqrt{3} \cdot K_a \cdot K_{z-pf} \cdot K_{g-pf}} - 1 \right]^{0.833} \tag{7.6}$$

Where:

- D_{pp-pf} is the phase to earth clearance with power frequency voltages $[m]$
- U is the maximum voltage of the system $[kV]$
- K_a is the altitude factor
- K_{z-pf} is the deviation factor for power frequency voltages being 0.910 according to [3]
- K_{g-pf} is the gap factor for power frequency voltages being 1.26 according to [3]

7.2 Mid-span clearances

Designing a reliable tower is not limited only to the electrical clearances, but also to the mid-span clearances, which are the distances between the phase conductors in the middle of a span to avoid flash-overs under extreme wind actions.

Therefore, to calculate the mid-span clearances, the swing angle of the conductor is calculated to determine the most unfavorable position of the phase conductors in the span.

Swing angle

The swing angle is calculated to consider possible wind actions on the conductors and insulators; in this methodology, it is calculated considering an extreme wind speed. The swing angle defines a swung position of the conductors that determines the mid-span clearance. Consequently, using Equations (7.7) and (7.10) the swing angles of either a phase conductor or an insulator with a conductor are calculated for a wind speed of 120 km/h. Figure 7.1 shows an illustration of a swing angle of an insulator.

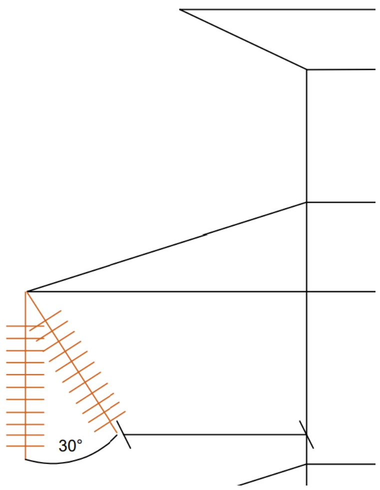

Figure 7.1: The swing angle

Swing angle for a conductor:

$$\phi_c = tang^{-1}\left[\frac{(\rho/2)\cdot C_c \cdot V_R^2 \cdot G_L \cdot D \cdot a_w}{m_C \cdot g \cdot a_{wg}}\right] \tag{7.7}$$

Where:

- ϕ_c is the swing angle for a conductor in degrees
- ρ is the air density depending on temperature, humidity and altitude calculated using Equation (7.8) $[kg/m^3]$
- C_c is the drag factor equal to 1.0
- V_R is the reference wind speed taken as 33.3 $[m/s]$
- G_L is the span factor taking into account the effect of wind span, it is calculated in Equation (7.9)
- D is the diameter of the conductor $[m]$
- a_w is the wind span $[m]$
- a_{wg} is the weight span $[m]$
- m_c is the conductor mass per unit length $[kg/m]$
- g is the gravity 9.81 $[m/s^2]$

The air density is calculated using the following equation according to [3] :

$$\rho = \rho_0 \left[\frac{298}{T+273}\right] exp(-0.00012 \cdot H) \tag{7.8}$$

Where:

- ρ is the air density $[kg/m^3]$

- T is the ambient temperature in Celsius
- ρ_0 is the density at 15°C equal to 1.225 $[kg/m^3]$
- H is the altitude above sea level $[m]$

The span factor used to calculate the swing angle is calculated according to the IEC standard [18] as follows:

$$G_L = (4 \cdot 10^{-10} \cdot a_w^3) - (5 \cdot 10^{-7} \cdot a_w^2) - (10^{-4} \cdot a_w) + 1.0403 \quad (7.9)$$

Where:

- G_L is the span factor
- a_w is the wind span $[m]$

Swing angle for an insulator:

$$\phi_{ins} = tang^{-1}\left[\frac{(\rho/2) \cdot C_c \cdot V_R^2 \cdot G_L \cdot D \cdot a_w + Q_{Wind}/2}{W_C + W_{ins}/2}\right] \quad (7.10)$$

Where:

- ϕ_{ins} is the swing angle for an insulator in degrees
- ρ is the air density depending on temperature, humidity and altitude calculated using Equation (7.8) $[kg/m^3]$
- C_c is the drag factor equal to 1.0
- V_R is the reference wind speed taken as 33.3 $[m/s]$
- G_L is the span factor taking into account the effect of wind span, calculated in Equation (7.9)
- D is the diameter of the conductor $[m]$
- a_w is the wind span $[m]$
- Q_{Wins} is the wind load on the insulator set calculated using Equation (7.11) $[N]$
- W_c is the effective conductor weight $[N]$
- W_{ins} is the dead weight of the insulator set $[N]$

The wind load on the insulator set is calculated according to the IEC standard [18]

$$Q_{Wins} = P \cdot C_{ins} \cdot A_{ins} \quad (7.11)$$

Where:

- Q_{Wins} is the wind load on the insulator set $[N]$
- P is the wind pressure calculated using Equation (7.12) $[Pa]$
- C_{ins} is the drag factor of the insulator being 1.2

- A_{ins} is the area exposed by the insulator set; the area is considered as a rectangle multiplying the insulator diameter with its length $[mm]$

The wind pressure is calculated based on the air density according to the IEC 60826 standard [18]:

$$P = 1/2 \cdot \rho \cdot V_R^2 \tag{7.12}$$

Where:

- P is the wind pressure $[Pa]$
- ρ is the air density depending on temperature, humidity and altitude calculated using Equation (7.8) $[kg/m^3]$
- V_R is the reference wind speed taken as 33.3 $[m/s]$

Calculating the swing angle for a conductor, allows the calculation of the mid-span clearances, both phase-phase and phase-earth. [3]

Phase-phase midspan clearance:

The phase to phase mid-span clearance is the distance between two parallel phase conductors and it is calculated as follows:

$$c_{min-pp} = K_c\sqrt{f_c + l_k} + 0.75 \cdot D_{pp} \tag{7.13}$$

Where:

- c_{min-pp} is the phase to phase mid-span clearance $[m]$
- K_c is the swinging coefficient determined based on the swing angle in Table 7.2
- f_c is the sag of the conductor $[m]$
- l_k is the length of the insulator set swinging orthogonally to the line direction $[m]$
- D_{pp} is the phase-phase electrical clearance calculated using Equation (7.1) $[m]$

Table 7.2: The minimum standard clearances pp and pe [Source EN]

Swing angle $\phi[°]$	Swinging coefficient K_c
⩽40	0.6
⩽55	0.62
⩽65	0.65
>65	0.7

Phase-earth midspan clearance:

The phase to earth mid-span clearance is the distance between the phase conductors and the earth wire and it is calculated as follows:

$$c_{min-pe} = K_c\sqrt{f_c + l_k} + 0.75 \cdot D_{pe} \tag{7.14}$$

Where:

- c_{min-pe} is the phase to earth mid-span clearance $[m]$
- K_c is the swinging coefficient determined based on the swing angle in Table 7.2
- f_c is the sag of the conductor $[m]$
- l_k is the length of the insulator set swinging orthogonally to the line direction $[m]$
- D_{pe} is the phase-earth electrical clearance calculated using Equation (7.4) $[m]$

Finally, after calculating the phase to phase and phase to earth clearances at the middle of the span, the mid-span clearance of each tower is considered as the maximum between those of its previous and next spans.

7.3 Safety distances

As mentioned at the beginning of this chapter, some safety distances are determined to ensure a reliable design of the overhead line. Among these safety distances, the minimum ground clearance and the distance to object as seen in Figure 7.2 are determined.

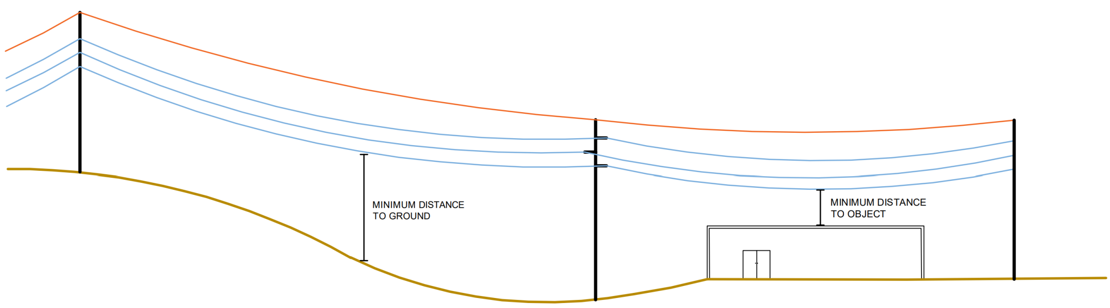

Figure 7.2: Safety distances of the line

Minimum ground clearance:

The minimum ground clearance is the minimum distance to the ground that all the catenaries in the line's spans must respect. This distance is calculated considering the electrical phase to earth clearance and it is considered from the lowest point of the conductor catenary. Accordingly, the minimum ground clearance is calculated using Equation (7.15).

$$d_{min} = D_{pe} + a_{add} \tag{7.15}$$

Where:

- d_{min} is the minimum distance to the ground $[m]$
- D_{pe} is the phase-earth electrical clearance calculated using Equation (7.4) $[m]$
- a_{add} is the additional safety distance according to [3] being 5 $[m]$

Minimum distance to object:

The minimum distance to object is the minimum distance that a user should consider in case of crossing an object such as a building in the line's path. This distance is calculated using Equation (7.16) as follows:

$$D_{add} = D_{pe} + a_{add} \tag{7.16}$$

Where:

- D_{add} is the minimum distance to the ground $[m]$
- D_{pe} is the phase-earth electrical clearance calculated using Equation (7.4) $[m]$
- a_{add} is the additional safety distance according to [3] being 10 corresponding to a non-fire resistant roof $[m]$

Chapter 8

Tower geometry

The top-geometry of the line's towers is determined based on all the parameters explained in the previous chapters. The clearances between the conductors, the clearances between the conductor and the earthed parts of the tower, the mid-span clearances, and the effect of the wind action on the conductor and the insulator are all considered when designing a tower's top-geometry to ensure the reliability of the line.

In this chapter the line's towers top-geometry calculation is explained and the different parameters that define the tower's parts are described.

8.1 General procedure

After selecting an adequate tower based on the voltage and capacity as explained in Chapter 4, the top-geometry of the tower is determined based on the electrical clearances. In order to define the final geometries for each type of tower designed in this methodology, the following procedure is followed:

- The tower is defined with nodes that represent the possible connections of the conductor and insulator with the tower's cross-arms and body, an example of these nodes is illustrated in Figure 8.1.
- The coordinates of each node are determined based on the electrical and mid-span clearances calculated previously
- Based on the tower category, either suspension or angle, some parameters such as the swing angle is calculated to define the peak distance
- From the nodes' coordinates, the tower's components and distances are calculated:
  - the tower's cross-arm distance
  - the peak distance
  - the distance between the cross-arms vertically
  - the width of all the towers' body is considered as 1m.
- Based on the tower type, the top-geometry calculated is ,then, compared with a standard catalog of towers [19].

- If a standard tower that meets this methodology's design criteria is found, it gets selected, if not, the tower calculated based on the procedure above is considered instead.

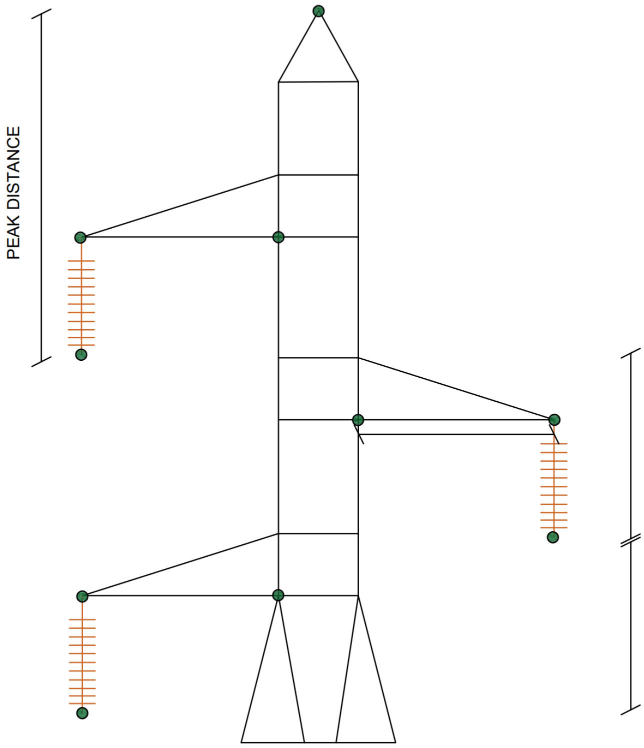

Figure 8.1: Top-geometry of an S tower

8.2 Peak distance calculation

The peak distance as shown in Figure 8.1 is the vertical distance between the highest phase conductor to the earth wire, considering the swing angle in the most unfavorable conditions. The peak distance is calculated using Equation (8.1) depending on the tower type that defines the position of the insulator; if it is a suspension or tension insulator.

Moreover, this distance is compared against the phase-earth midspan clearance calculated previously to consider the highest distance and ensure the respect of all the clearances.

$$D_{peak} = \frac{D_{pe} + (l_{ins} \cdot sin(\phi))}{tan(\alpha)} \tag{8.1}$$

Where:

- D_{peak} is the peak distance $[m]$
- D_{pe} is the electrical phase-earth distance calculated using Equation (7.4) $[m]$
- l_{ins} is the insulator set length $[m]$
- ϕ is the swing angle in degrees
- α is the shield angle of the earth wire in degrees, being 30°

8.3 Standard towers top-geometry

As explained in the general procedure of calculating the tower top-geometry, the selection of a standard tower is possible when it respects the design criteria. In this methodology, similar towers from Imedexsa's catalog [19] to the designed towers were selected, based on the shape, the voltage and the number of circuits.

The dimensions of the standard towers listed in tables 8.1 to Table 8.5 are used to select the final tower's top-geometry for the MV and HV voltage levels.

Table 8.1: Tower type Atorinillada N shape. [Source: Imedexsa [19]]

Type	a	b	c	h
N0	1	1.2	1.25	1.5
N1	1.25	1.2	1.5	1.5
N2	1.5	1.8	1.75	1.5

Table 8.2: Tower type Condra S shape. [Source: Imedexsa [19]]

Type	a	b	c	h
S3	3	3.3	3.2	–
S4	4.1	4.4	4.3	–
S5	4.1	5.5	3.3	–
S3C	3	3.3	3.2	4.3
S4C	4.1	4.4	4.3	5.9
S5C	4.1	5.5	3.3	5.9

Table 8.3: Tower representing the Pi tower. [Source: Imedexsa [19]]

Type	a	b	c	h
D3	3	13.5	7.5	4.3
D5	3.2	15	8.6	4.3
D7	3.8	17	9.4	5.5

Table 8.4: Tower type Condor N Doble. [Source: Imedexsa [19]]

Type	b	a/c	d-e
1	3.3	3	4.3
2	4.4	3.2	5.2
3	5.5	3.6	5.9
4	–	3.8	6.6
5	–	4.1	3.3-3
6	–	4.3	4.4-3
7	–	4.6	5.5-3
8	–	4.9	–

Table 8.5: Tower type Icaro N shape. [Source: Imedexsa [19]]

Type	b	a/c	d-e
1	5.8	4.5	7.2
2	–	5	8.6
3	–	6	4.9-3.5
4	–	6.5	6.2-3.5

Chapter 9

Electrical calculation

The main purpose of an overhead line is to carry the electrical energy from the generation point to the delivery point. Therefore, calculating the electrical characteristics of the line is essential in order to ensure a reliable transmission of the energy. A poorly designed overhead line from an electrical perspective could cause instability and excessive losses.

The quality of the design will depend on the conductor selection and the circuit arrangement, which will determine the electrical parameters of the line. This chapter presents the basic formulae for calculating the electrical parameters of the line, as well as the voltage drop, power losses and power factor.

9.1 Electrical models

When calculating the electrical behavior of an overhead line, the literature proposes three different calculation methods with different complexity and accuracy. The selection of the model typically depends on the length of the overhead line.

- **Short-Line model:** The equivalent circuit shown in Figure 9.1 only takes into account the effect of the resistance and the reactance of the conductor, disregarding the effect of the capacitance of the line. The Short-Line model is only used for lengths up to 80 km, losing accuracy for longer lines.

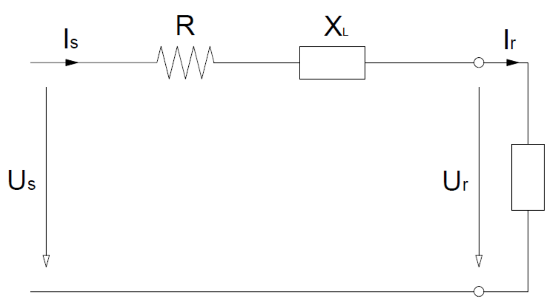

Figure 9.1: Equivalent circuit of the short line model

- **Pi Model:** Takes into account the effect of the capacitance on the overhead line. This model in Figure 9.2 considers that the electrical parameters of the line are concentrated and not distributed along the line, with better accuracy than the one provided by the Short-Line model, but the complexity of the calculation increases. The Pi model is used for lines with a length up to 300 km.

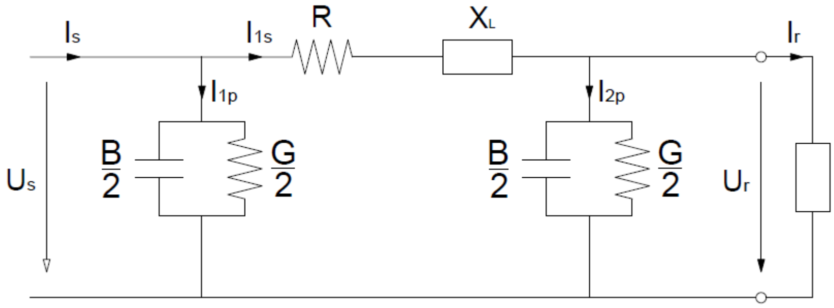

Figure 9.2: Equivalent circuit of the pi model

- **Distributed Parameters Model** This model represents the exact mathematical model for an overhead line with evenly distributed parameters across the line, providing accurate results even for lengths over 300 km. The distributed parameters model can be represented by either exponential functions or hyperbolic functions and the equivalent circuit is shown in Figure 9.3

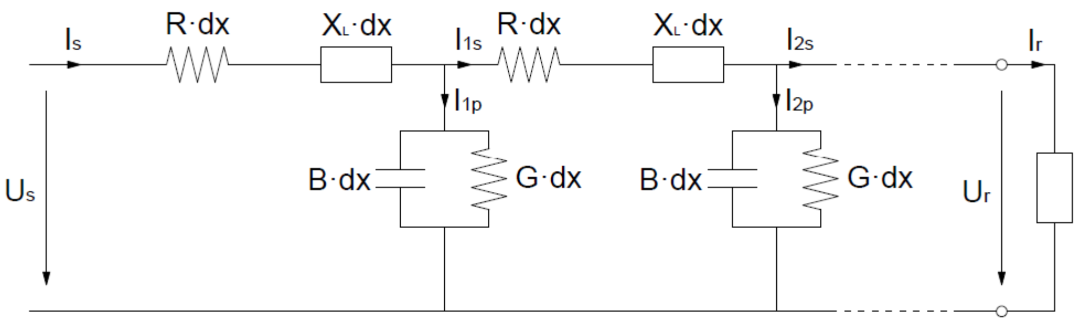

Figure 9.3: Equivalent circuit of the distributed parameters model

9.1.1 Distributed Parameters Model

After analyzing the advantages and disadvantages of the three electrical models, the distributed parameters model was selected due to its accuracy, especially for longer lines. Therefore, this section will be referring to the equivalent circuit shown in Figure 9.3.

The model is based on four electrical parameters: resistance (R), inductance (X), susceptance (B) and conductance (G), which will be discussed in later sections of the chapter. A typical simplification that is done is to not consider the conductance G due to its residual effect on the result.

In order to calculate the behavior of the circuit, the differential equations of the electrical model have to be solved, knowing the values of the voltage and current at the sending end (substation point) V_s and I_s.

Equations (9.1) and (9.2) represent the differential equations of the distributed parameters model:

$$-\frac{d\vec{U}}{dx} = (R + jX) \cdot \vec{I} \tag{9.1}$$

$$-\frac{d\vec{I}}{dx} = (G + jB) \cdot \vec{U} \tag{9.2}$$

From the previous expressions, the following equations can be deduced [3] :

$$\vec{U} = \left(\frac{\vec{U_s} - \vec{I_s} \cdot \vec{Z_0}}{2}\right) \cdot \exp(\gamma \cdot x) + \left(\frac{\vec{U_s} + \vec{I_s} \cdot \vec{Z_0}}{2}\right) \cdot \exp(-\gamma \cdot x) \tag{9.3}$$

$$\vec{I} = \left(\frac{\vec{I_s} - \vec{U_s}/\vec{Z_0}}{2}\right) \cdot \exp(\gamma \cdot x) + \left(\frac{\vec{I_s} + \vec{U_s}/\vec{Z_0}}{2}\right) \cdot \exp(-\gamma \cdot x) \tag{9.4}$$

Where:

- $\vec{U}$ is the phase to earth voltage at the receiving point
- $\vec{I}$ is the current at the receiving point
- $\vec{U_s}$ is the phase to earth voltage at the sending point
- $\vec{I_s}$ is the current at the sending point
- γ is the propagation constant of the line which is defined as

$$\gamma = \sqrt{(R + jX) \cdot (G + jB)} \tag{9.5}$$

- $\vec{Z_0}$ is the characteristic impedance of the line which is defined as

$$\vec{Z_0} = \sqrt{\frac{R + jX}{G + jB}} \tag{9.6}$$

Equations (9.3) and (9.4) represent the distributed parameters model using exponential equations. However, there is another way to represent the equations using hyperbolic functions, that derives in the following expressions [3]:

$$\vec{U} = \vec{U_s} \cdot \cosh\gamma - \vec{I_s} \cdot \vec{Z_0} \cdot \sinh\gamma \tag{9.7}$$

$$\vec{I} = \vec{I_s} \cdot \cosh\gamma - \frac{\vec{U_s}}{\vec{Z_0}} \cdot \sinh\gamma \tag{9.8}$$

9.2 Electrical Parameters

The aforementioned electrical model presents an electrical circuit with different components, which are used to calculate the voltage and current at the receiving end of the overhead line. Even though the distributed parameters model is very accurate, the electrical parameters used in it must be estimated accordingly in order to obtain a reliable result.

It is important to note that the electrical parameters will not only depend on the conductor's material and composition, but also on their geometrical disposition throughout the line.

9.2.1 Geometrical Mean Distance

The geometrical mean distance (GMD) is the equivalent distance between the conductor bundles of an overhead line, and will affect directly the values of the inductance and the capacitance of the overhead line.

The calculation of the GMD depends on the number of circuits installed in the line. This section only covers the calculation of the GMD of configurations with one circuit and with two circuits, which are the most widely used configurations.

In Figure 9.5, an example configuration of a one circuit configuration is shown, with the three phase conductors separated by distances D_{ab}, D_{ac} *and* D_{bc}.

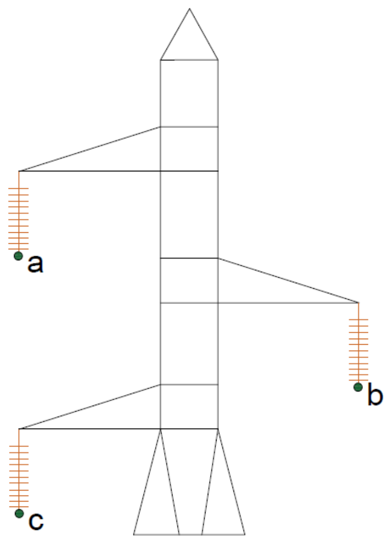

Figure 9.4: Phases of a tower with one circuit for the GMD calculation

The GMD in this case can be calculated according to Equation (9.9) , where D_{ij} refers to the distance between phase i and phase j :

$$GMD = \sqrt[3]{D_{ab} \cdot D_{ac} \cdot D_{bc}} \tag{9.9}$$

The two circuits configuration is shown in Figure 9.5, where the first circuit is formed by conductors a, b and c and the second circuit is formed by conductors a', b' and c'.

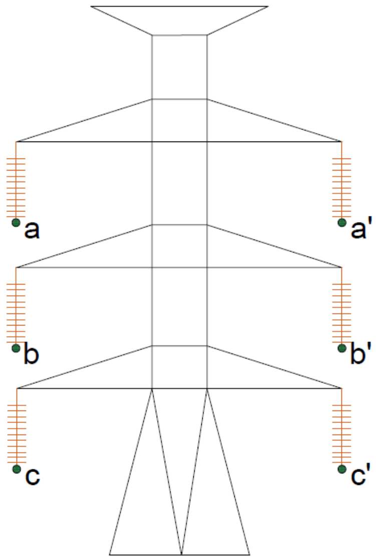

Figure 9.5: Phases of a tower with two circuits for the GMD calculation

In this case, the GMD will be calculated according to Equations (9.10), (9.11), (9.12) and (9.13):

$$D_{AB} = \sqrt[4]{D_{ab} \cdot D_{ab'} \cdot D_{a'b} \cdot D_{a'b'}} \tag{9.10}$$

$$D_{BC} = \sqrt[4]{D_{bc} \cdot D_{bc'} \cdot D_{b'c} \cdot D_{b'c'}} \tag{9.11}$$

$$D_{CA} = \sqrt[4]{D_{ca} \cdot D_{ca'} \cdot D_{c'a} \cdot D_{c'a'}} \tag{9.12}$$

$$GMD = \sqrt[3]{D_{AB} \cdot D_{BC} \cdot D_{CA}} \tag{9.13}$$

Another GMD that will be used in the inductance calculation is the one that establishes a relationship between the same phases of both circuits, defined by

$$GMD_{pp} = \sqrt[3]{D_{aa'} \cdot D_{bb'} \cdot D_{cc'}} \tag{9.14}$$

The previous expressions calculate the GMD of the circuits at a specific point of the overhead line. However, the conductor's disposition will change throughout the line, resulting in different values for GMD for different points in the line. In order to obtain a more accurate model, an average of the GMDs across the overhead line is calculated.

The average GMD within a span can be obtained from the GMD of its neighbor towers, according to Equation (9.15) , with GMD_1 and GMD_2 being the GMD at the previous and next towers respectively. This operation can be performed because the variation of the GMD across the span is linear.

$$\overline{GMD}_{span} = \frac{GMD_1 + GMD_2}{2} \tag{9.15}$$

Therefore, the average GMD of the entire overhead line can be calculated as a weighted average, considering the span length as the weight of the function:

$$\overline{GMD}_{ohl} = \frac{\sum_{i=1}^{spans}\left(\overline{GMD}_i \cdot L_i\right)}{L_{ohl}} \tag{9.16}$$

Where:

- $\overline{GMD}_{ohl}$ is the average GMD of the entire overhead line [m]
- $\overline{GMD}_i$ is the average GMD of span i [m]
- L_i is the length of span i [m]
- L_{ohl} is the sum of the length of all the spans in the overhead line [m]

Similarly, GMD_{pp} can also be calculated as a weighted average throughout the overhead line with Equation (9.17) , in which $\overline{GMD}_{pp_i}$ is the average GMD_{pp} in a span, calculated from Equation (9.15)

$$\overline{GMD}_{pp_{ohl}} = \frac{\sum_{i=1}^{spans}\left(\overline{GMD}_{pp_i} \cdot L_i\right)}{L_{ohl}} \tag{9.17}$$

9.2.2 Geometrical Mean Radius

The Geometrical Mean Radius (GMR) is the average of the distances between the conductors within the same bundle, which will affect the calculation of the inductance and capacitance across the overhead line.

Figure 9.6 shows a bundle of four conductors with a separation d between them (the separation will be 400 mm by default for the calculation model).

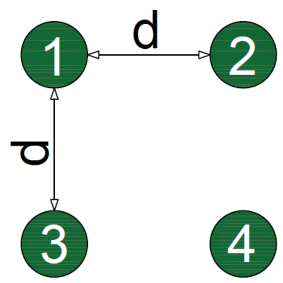

Figure 9.6: Four conductors bundle

Equation (9.18) shows the general expression to calculate the GMR in a symmetrical configuration:

$$GMR = \sqrt[n]{r' \cdot \prod_{i=2}^{n} d_{1\to i}} \tag{9.18}$$

Where:

- r' is the GMR of a single conductor, defined as $r' = \exp(-0.25) \cdot r$ with r being the radius of the conductor [m]
- n is the number of conductors in the bundle

- $d_{1\to i}$ is the distance between the first conductor and conductor i [m]

For the capacitance calculation, the radius r' will be substituted by the actual radius of the conductor r, as shown in Equation (9.19)

$$GMR_C = \sqrt[n]{r \cdot \prod_{i=1}^{n} d_{1\to i}} \tag{9.19}$$

The previous equation can be rewritten for different number of conductors in the bundle, where d is the separation between conductors and r is the radius of the conductor.

$$GMR_1 = 0.7788 \cdot r \tag{9.20}$$

$$GMR_{1C} = r \tag{9.21}$$

$$GMR_2 = 0.8825 \cdot \sqrt{r \cdot d} \tag{9.22}$$

$$GMR_{2C} = \sqrt{r \cdot d} \tag{9.23}$$

$$GMR_3 = 0.9200 \cdot \sqrt[3]{r \cdot d^2} \tag{9.24}$$

$$GMR_{3C} = \sqrt[3]{r \cdot d^2} \tag{9.25}$$

$$GMR_4 = 1.0244 \cdot \sqrt[4]{r \cdot d^3} \tag{9.26}$$

$$GMR_{4C} = 1.0905 \cdot \sqrt[4]{r \cdot d^3} \tag{9.27}$$

The GMR throughout the overhead line will remain constant, as the bundle disposition will not change at any point of the line. Therefore, there is no need to calculate an average in this case.

9.2.3 Resistance

The resistance of the overhead line is one of the most influencing parameters due to its direct dependency with the power losses. A high resistance value will yield high power losses, resulting in a poor design of the line. On the other hand, low resistance conductors have larger sections, increasing the costs and the mechanical loads.

In order to compute the resistance of the entire overhead line, the calculated AC resistance from Equation (2.1) will be used, as it represents the AC resistance of a single conductor.

The equation that is used to calculate the resistance of the entire overhead line is the following:

$$R = \frac{R_{AC}}{n_c \cdot n_s} \cdot l \tag{9.28}$$

Where:

- R is the resistance of the entire line [Ω]
- R_{AC} is the AC resistance of a single conductor [Ω/m]
- n_c is the number of circuits
- n_s is the number of subconductors
- l is the length of the line $[m]$

As it can be seen from Equation (9.28), the resistance of the overhead line has a linear dependency on the number of conductors of the line.

9.2.4 Inductance and Reactance

A current carrying conductor will produce a magnetic field around itself, resulting in an inductance in AC systems due to the variation of the conductor's current. When more than one conductor coexist in an electrical configuration, the magnetic field that one conductor generates affects the other, meaning that there will be a geometrical relationship affecting the inductance of the overhead line.

Equations (9.29) and (9.30) refer to the calculation of the inductance for simplex and duplex configurations respectively.

$$L = \frac{\mu_0}{2\pi} \cdot \ln \frac{GMD}{GMR} \cdot l \tag{9.29}$$

$$L = \frac{\mu_0}{2\pi} \cdot \ln \left(\frac{GMD}{\sqrt{GMR} \cdot \sqrt{GMD_{pp}}} \right) \cdot l \tag{9.30}$$

Where:

- L is the inductance of a fully transposed overhead line [H]
- μ_0 is the vacuum permeability [H/m]
- GMD is the Geometrical Mean Distance calculated with Equation (9.16) [m]
- GMR is the Geometrical Mean Radius calculated with Equation (9.18) [m]
- GMD_{pp} is the Geometrical Mean Distance of same phases in a duplex configuration calculated with Equation (9.17) [m]
- l is the length of the line $[m]$

In order to understand Equation (9.30), it is important to take into account that each circuit's phase will have a counterpart in the other circuit. For the calculation model, both phases' (a and a') voltage and current will be considered to have the same argument and power factor. Knowing this, they are considered to be the same phase when calculating the GMR. If this was the case, the GMR according to Equation (9.18) would be calculated as:

$$GMR_{2circuits} = \sqrt[2n]{r' \cdot \prod_{i=2}^{n} d_{1\to i} \cdot \prod_{i'=1}^{n} d_{1\to i'}} = \sqrt[2n]{r' \cdot \prod_{i=2}^{n} d_{1\to i}} \cdot \sqrt[2n]{\prod_{i'=1}^{n} d_{1\to i'}} \tag{9.31}$$

This expression can be simplified using Equations (9.18) and (9.14):

$$GMR_{2circuits} = \sqrt{GMR} \cdot \sqrt{GMD_{pp}} \tag{9.32}$$

Where $d_{1\to i}$ is the distance between the first conductor of the first circuit to the conductors in its bundle and $d_{1\to i'}$ is the distance between the first conductor of the first circuit and the conductors of the second circuit's bundle.

Once the inductance of the line has been obtained, the inductive reactance of the line can be calculated according to Equation (9.33)

$$X_L = 2\pi \cdot f \cdot L \tag{9.33}$$

Where:

- X_L is the reactive inductance per unit length of the fully transposed overhead line [Ω]

- f is the frequency of the line [Hz]
- L is the inductance of the line

9.2.5 Impedance

The impedance of the transmission line will be calculated using Equation (9.34)

$$\vec{Z} = R + jX_L \tag{9.34}$$

Where:

- $\vec{Z}$ is the impedance of the line [Ω]
- R is the resistance of the line [Ω]
- X_L is the inductive reactance of the line [Ω]

9.2.6 Capacitance and Susceptance

The capacitance of an overhead line can be calculated using Equations (9.35) and (9.36) :

$$C = \frac{2\pi\epsilon_0}{\ln\left(\frac{GMD}{GMR_C \cdot \sqrt{1+(GMD/2h_M)^2}}\right)} \cdot l \approx \frac{2\pi\epsilon_0}{ln\left(\frac{GMD}{GMR_C}\right)} \cdot l \tag{9.35}$$

$$C = \frac{2\pi\epsilon_0}{ln\left(\frac{GMD}{GMR_C \cdot GMD_{pp}}\right)} \cdot l \tag{9.36}$$

Where:

- C is the capacitance of the overhead line [F]
- ϵ_0 is the dielectric constant [F/m]
- GMD is the geometrical mean distance according to Equations (9.9) and (9.13) [m]
- GMR_C is the geometrical mean radius for the capacitance according to Equation (9.19) [m]
- GMD_{pp} is the Geometrical Mean Distance of same phases in a duplex configuration calculated with Equation (9.17) [m]
- h_M is the average height of the conductor throughout the overhead line, calculated for every span. This is obtained by averaging the vertical distance between the catenary curve (see Section 10.3 for more details) and the terrain throughout the overhead line. [m]
- l is the length of the line $[m]$

Equation (9.35) shows a precise and a simplified version for the calculation of the capacitance in a simplex configuration. For conductors with considerable height above ground, both equations will yield similar results, but for lower conductors, the differences might go up to a 5 to 10% . Therefore, the complete Equation (9.35) has been selected for simplex configurations.

Regarding duplex configuration, the simplified version in Equation (9.36) has been used due to a slightly higher complexity in its calculation.

Once the capacitance has been calculated, the capacitive reactance and susceptance can be obtained using Equations (9.37) and (9.38)

$$X_C = \frac{1}{2\pi \cdot f \cdot C} \tag{9.37}$$

$$B = 2\pi \cdot f \cdot C \tag{9.38}$$

Where:

- X_C is the capacitive reactance [Ω]
- f is the frequency of the line [Hz]
- C is the capacitance per unit length [F/m]
- B is the susceptance per unit length [Ω^{-1} m^{-1}]

9.3 Voltage drop

The voltage drop across an overhead line is defined as the difference between the voltage at the receiving and the voltage at the sending end. This is an important value that will determine the quality of the transmission, and will be limited to a 5% maximum voltage drop. The general approach in the literature is to respect this 5% and sometimes even a 7.5% or a 10% for extreme designs.

From the distributed parameters model in Subsection 9.1.1, the voltages and currents at the sending and receiving end can be obtained. The power factor at the sending end will be considered to be equal to the one established by the user in the interface. Therefore, the voltage and current at the sending end can be determined as:

$$\vec{U_s} = U \tag{9.39}$$

$$\vec{I_s} = \frac{S}{\sqrt{3}U}(\cos\phi_s + j\sin\phi_s) \tag{9.40}$$

Where:

- U_s is the phase to phase voltage at the sending end [V]
- U is the phase to phase voltage level of the overhead line [V]
- I_s is the current at the sending end [A]
- S is the apparent power of the line [MVA]
- ϕ_s is the power factor angle at the sending end [rad]

Having the electrical parameters calculated, the voltage and current at the receiving end can be calculated using Equations (9.7) and (9.8) respectively. The voltage drop can then be obtained using Equations (9.41) and (9.42) , where ΔV is the voltage drop, U_s is the voltage at the sending end and U_r is the voltage at the receiving end.

$$\Delta U = |U_s| - |U_r| \tag{9.41}$$

$$\Delta U(\%) = \frac{|U_s| - |U_r|}{|U_s|} \cdot 100 \tag{9.42}$$

9.4 Power factor

The power factor calculation of grid connected transmission lines is a complex problem because it involves different generation facilities connected simultaneously affecting the power factor of the line. Because information about other facilities is not available, the power factor calculation is based on the fact that the current and voltage at the substation are known, according to Equations (9.39) and (9.40).

Therefore, the voltage and current at the receiving end can be calculated with the distributed parameters model, giving out a complex value for the voltage and for the current at the receiving end. The phase difference between these two values will determine the power factor at the receiving end:

$$\cos\phi_r = \cos\left(arg\vec{U_r} - arg\vec{I_r}\right) \tag{9.43}$$

Where:

- $\cos\phi_r$ is the power factor at the receiving end
- $\vec{U_r}$ is the voltage at the receiving end [V]
- $\vec{I_r}$ is the current at the receiving end [I]

9.5 Losses

The purpose of an overhead line is to transmit energy from a generation point to a delivery point. The power losses during the transmission and distribution will reduce the energy delivered with the same proportion. This means that, if 5% of the power is lost in the overhead line, then 5% of the energy carried will also be lost. Because of this, it is really important to reduce the power losses as much as possible.

The electrical losses in an overhead line are generally caused by two physical phenomena: the Joule effect, due to the conductor's resistance and the Corona effect, caused by the ionization of the air around the conductor. The accepted losses for an overhead line will always be lower than 5% combining the Joule effect and the corona effect.

9.5.1 Joule effect

The well known Joule effect losses appear when a current flows through a conductor with a resistance, dissipating energy as heat. The voltage and current of both, sending and receiving ends can be calculated using the Equations (9.7) and (9.8) from the hyperbolic distributed parameters model. The Joule losses can then be calculated according to Equations (9.44), (9.45), (9.46) and (9.47).

$$P_s = U_s \cdot I_s \cdot \sqrt{3} \cdot \cos\phi_s \tag{9.44}$$

$$P_r = U_r \cdot I_r \cdot \sqrt{3} \cdot \cos\phi_r \tag{9.45}$$

$$\Delta P = P_r - P_s \tag{9.46}$$

$$\Delta P(\%) = \frac{P_r - P_s}{P_s} \cdot 100 \tag{9.47}$$

Where:

- P_s is the power at the substation [W]
- P_r is the power at the end of the line [W]
- ΔP is the power losses [W]
- U_s is the voltage at the substation [V]
- U_r is the voltage at end of the line [V]
- ϕ_s is the power factor at the substation
- ϕ_r is the power factor at the end of the line according to Equation (9.43)

9.5.2 Corona losses

Corona effect happens when the air surrounding a conductor gets ionized, becoming conductive and dissipating some of the overhead line's energy. This effect usually occurs in high voltage lines, where the disruptive voltage for air to be ionized is surpassed. The corona effect in an overhead line is usually calculated according to Peek's empirical formula [20] , obtaining first the corona disruptive voltage and then calculating the corona losses if this disruptive voltage is surpassed in the line.

The corona disruptive voltage is calculated according to Equation (9.48) , which is derived from Peek's formulae:

$$U_p = \sqrt{3} \cdot \frac{29.8}{\sqrt{2}} \cdot m_c \cdot \delta \cdot m_t \cdot r \cdot n \cdot \ln\frac{GMD}{r} \tag{9.48}$$

Where:

- U_p is the critical disruptive phase to phase voltage [kV]
- m_c is the rugosity coefficient of the conductor considered as 0.85 for stranded conductors
- δ is the air correction factor, calculated according to [3] with T being the temperature and H being the altitude. It is important to note that Peek establishes the unity of the air correction factor at standard conditions (25ºC and 1 atm) instead of normal conditions

$$\delta = \left(\frac{273 + 25}{T}\right) \cdot \exp\left(-0.00012 \cdot H\right) \tag{9.49}$$

- m_t is the weather correction factor, considered as 0.8 for rainy conditions
- r is the conductor's radius [cm]

- n is the number of conductors in the bundle
- GMD is the geometrical mean distance according to Equation (9.16) [cm]

If the maximum voltage of the overhead line surpasses the disruptive voltage, the Corona effect will occur. To calculate the losses, Peek's equation will be used:

$$P_{Corona} = \frac{241}{\delta}(f + 25)\sqrt{\frac{r}{GMD}}\left(\frac{U_{max} - U_p}{\sqrt{3}}\right)^2 \cdot 10^{-5} \tag{9.50}$$

Where:

- P_{Corona} is the power losses due to corona effect [W]
- δ is the air correction factor
- f is the frequency [Hz]
- r is the radius of the conductor [m]
- GMD is the geometrical mean distance of the line [m]
- U_{max} is the maximum voltage of the line [kV]
- U_p is the critical disruptive voltage between phase and earth according to Equation (9.48) [kV]

As a design requirement, the combination of both, Joule and Corona losses, cannot be higher than 5% . If this percentage is surpassed, the electrical configuration must be changed. One way to drastically reduce the effect of corona is by increasing the number of conductors per bundle, which will increase the disruptive voltage.

Chapter 10

Mechanical calculation

The mechanical calculation of an overhead line is an essential step in the design, ensuring that none of the elements will fail during almost every condition. An overhead line is a set of towers, conductors, insulators, earth wires, fittings and foundations, all of them subject to forces and weather conditions.

In this chapter, the mechanical calculation of the towers, conductors, earth wires and insulators will be explained, along with the design requirements for each one of them to prevent failure of the overhead line. One extra consideration is the strength coordination of the different elements to avoid that a failure in any component leads into a failure of the entire line.

All of the calculations that apply to conductors in this chapter will be also applicable to the earth wires.

10.1 Conductor Loads hypothesis

The elements of the overhead line are exposed to the different weather conditions, such as ice, wind and temperature. Although these conditions mostly depend on the location of the line, there will only be five hypotheses that will be addressed in this section according to IEC 60826 [18] and CIGRE Technical Brochure 273 [21]:

- **Wind:** When the elements of the overhead line are exposed to high wind speeds, there will be a transversal force in the conductors, which will be transferred to the towers and the insulators. The determination of the wind speed can usually be done from a statistical analysis of wind speed in the area, however, a wind speed of 33.3 m/s or 120 km/h has been selected, as it is a widely used value in some countries. The conductor's temperature used for this hypothesis is 10ºC. This is because IEC [18] establishes that maximum wind under average of the daily minimum temperatures (assumed as 10ºC) condition is the most restrictive one regarding wind.
- **Ice:** The second hypothesis considers the ice accretion in the conductors, which leads into a noticeable increase in their weight. The calculation of ice loads considers an ice thickness of 30 mm and an ice density of 900 kg/m^3 , with a conductor's temperature of -5ºC and without wind.
- **Heavy load:** The third hypothesis combines the effect of wind and ice simultaneously, yielding an increase in both vertical and transversal loads. Again, every country has a

specific way to calculate the combined wind and ice loads, but the general consensus is that the wind load under combined effects is a fraction of the total wind load of the first hypothesis. Therefore the conditions for combined loads are conductors with full ice load and 70% wind speed on them, with a conductor's temperature of -5ºC (IEC establishes that the least probable wind speed is between a 60% and a 85%).

- **EDS:** Stands for everyday stress, and refers to calm weather conditions, with a temperature of 15ºC and no wind or ice loads. Under EDS conditions, the objective is to study the fatigue caused by the effect of aeolian vibrations [18] [21] . Assuming that the conductors are equipped with vibration dampers, the allowable tensile strength of the conductors will be considered to be equal to 22% of the conductor's tensile strength (IEC specifies a range of values between 15% and 25% , but a 22% has been used to match the Spanish standard).
- **Maximum Temperature:** Under this hypothesis, the conductors are under maximum temperature conditions of 85ºC. Although the ambient temperature will never reach these values, the power carried by the overhead line will increase it, reaching higher temperature values. This hypothesis is mainly used to study the sagging of the conductor.

10.2 Loads calculation

In this section, the calculation of the loads per unit length for the aforementioned hypotheses is presented. These loads have to be calculated for the conductors, the earth wires and the insulators; hence all of them must be able withstand the required loading conditions.

10.2.1 Weight loads

When a conductor is placed in an overhead line, its weight will generate a vertical load at the attachment points of the towers. This load will depend in the mass per unit length of the conductor.

The equation that is used to calculate the weight loads of a conductor or earthing wire is the following:

$$Q_{weight} = m_c \cdot g \tag{10.1}$$

Where:

- Q_{weight} is the weight load [N/m]
- m_c is the mass per unit length of the conductor [kg/m]
- g is the gravity, with a value of 9.81 [m/s^2]

10.2.2 Wind loads

When there is wind in an overhead line, it produces a force in the components of the line in the direction of the wind. As stated previously, the wind estimation can be obtained from meteorological measurements, considering a certain return period (see IEC 60826, section 6 for more information [18]). When this information is not available, a common approach is to use a specific value of wind speed that will ensure the safety requirements of the overhead line, in this case 120 km/h.

From the wind speed, the wind pressure can be obtained from Equation (10.2) extracted from IEC:

$$q_0 = \frac{1}{2} \cdot \tau \cdot \mu \left(V_R\right)^2 \tag{10.2}$$

Where:

- q_0 is the wind pressure [Pa]
- τ is the air density correction factor, considered as 1 (see table 6 of [18] for more details)
- μ is the air mass per unit volume, which is equal to 1.225 [kg/m^3]
- V_R is the wind velocity, which is considered to be in terrain category B [m/s]

Having the wind pressure from the previous equation, the wind load in the conductor can be calculated as:

$$Q_{wind} = q_0 \cdot C_{xc} \cdot G_c \cdot G_L \cdot d \cdot \sin^2 \Omega \tag{10.3}$$

Where:

- Q_{wind} is the wind load per unit length [N/m]
- C_{xc} is the drag coefficient, which is considered to be equal to 1
- G_c is the combined wind factor for conductors, which is not considered because it represents the loads of all three conductors in the tower (Equation (10.3) refers to a single conductor)
- G_L is the span factor, which has been considered equal to 1
- d is the diameter of the conductor [m]
- Ω is the angle between the wind direction and the conductor, which is considered to be equal to 90°, meaning that the wind will be perpendicular to the conductor

The final equation that is used to calculate the wind loads per unit length in conductors is the following:

$$Q_{wind} = q_0 \cdot d \tag{10.4}$$

The effect of the wind also generates loads in the overhead line's insulators, with a leaser effect in the general design. The expression that is used to calculate the wind loads acting on insulator strings is:

$$Q_{wind,ins} = q_0 \cdot C_{xi} \cdot G_t \cdot S_i \tag{10.5}$$

Where:

- $Q_{wind,ins}$ is the wind load at the insulator [N]

- C_{xi} is the drag coefficient of insulators, which is equal to 1.2
- G_t is the combined wind factor, which is also disregarded since it takes into account the effect of the wind load for the three insulator strings of the tower.
- S_i is the area of the insulator considering it to be a rectangle. It can be calculated by multiplying the length of the insulator and the diameter of one of its elements. [m^2]

10.2.3 Ice loads

The ice loads in an overhead line consists of frozen water that adheres to the different elements, increasing the weight that these elements have to withstand. There are two different types of ice: precipitation ice and cloud ice. Although the density of these two types of ice is different, and some designers might take this into account, this calculation model will only consider ice with a density of 900 kg/m^3 .

According to IEC 60826 [18], the ice loads per unit length can be calculated as:

$$Q_{ice} = 9.82 \cdot 10^{-3} \cdot \delta \cdot \pi \cdot t \cdot (d + t/1000) \tag{10.6}$$

Where:

- Q_{ice} is the ice loads per unit length [N/m]
- δ is the ice density, which is considered to be 900 [kg/m^3]
- t is the radial ice thickness, which is considered to be 30 [mm]
- d is the conductor diameter [m]

It is important to consider that the calculation of ice loads differs a lot depending on the country's standard. Because of this discrepancy, an ice thickness of 30 mm was selected, in order to be more conservative regarding the calculation, but trying to respect most standards.

In Table 10.1 for the same 30 mm diameter conductor, the ice loads per unit length might go from 6.5 N/m in Greece up to 79 N/m in Ireland. In order to have a conservative approach, the conditions selected for the ice loads are an ice thickness of 30 mm and an ice density of 900 kg/m^3.

Table 10.1: Ice loads for different countries for a conductor with a 30 mm diameter. [Source: [3]

]

Country	Ice thickness [mm]	Ice density [kg/m^3]	Ice load [N/m]
Belgium	20	600	19
Germany	Undefined	Undefined	8 - 32
Spain	Undefined	750	9.9 - 29.6
France	20	600	19
Greece	6.35 or 12.7	900	6.5 or 15.3
Ireland	40	900	79
Italy	12	920	19

The ice loads in the insulator strings are not calculated due to the small effect that they have in the calculation model.

10.2.4 Total loads

To take into consideration the different weather conditions, the combination of the weight of the conductor, the wind loads and the ice loads must be calculated, taking into account their direction. The ice and weight loads will be considered to be vertical loads, whereas the wind loads will be considered perpendicular to the conductor's trajectory.

The total loads per unit length are calculated according to:

$$Q = \sqrt{\left(Q_{weight} + Q_{ice}\right)^2 + Q_{wind}^2} \tag{10.7}$$

Where:

- Q is the total loads per unit length of the conductor [N/m]
- Q_{weight} is the weight loads per unit length of the conductor obtained from Equation (10.1) [N/m]
- Q_{ice} is the ice loads per unit length of the conductor according to Equation (10.6) [N/m]
- Q_{wind} is the wind loads per unit length of the conductor according to Equation (10.3) [N/m]

10.3 Catenary

10.3.1 Catenary curve calculation

When a conductor is placed between two attachment points with a tensile strength, it will naturally sag, following a curve called catenary, which is formed as a result of the vertical weight of the conductor along the span.

It is important therefore to calculate the catenary curve in order to ensure that the clearances and the tensile strengths are respected according to the IEC requirements. In order to calculate the catenary, two models are typically used in projects: the hyperbolic model and the parabolic model.

In this section, the hyperbolic model will be used, as it is more accurate than the parabolic one, but with higher complexity. In Figure 10.1, the catenary curve is shown with some of its characteristic points. All the equations will be referred to the coordinate system showed, considering the origin $x=0$ at the lowest point of the curve.

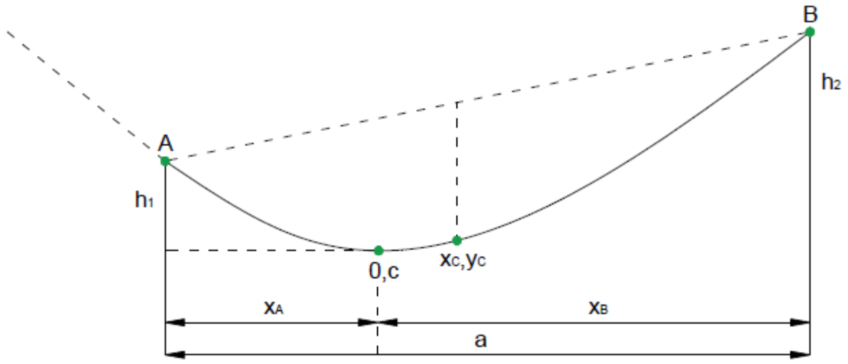

Figure 10.1: Catenary of a conductor

It is also important to note that this section will not study deeply the catenary equations. For more detailed calculations, check Chapter 14 of [3]

The main equation that describes the catenary curve according to the hyperbolic model is the following:

$$y = \frac{H}{w_c} \cdot \cosh \frac{w_c \cdot x}{H} \tag{10.8}$$

Where:

- y is the vertical coordinate of the catenary [m]
- H is the horizontal tension of the conductor [N]
- w_c is the weight per unit length of the conductor plus the ice if there was ice accretion [N/m]
- x is the horizontal coordinate of the catenary [m]

The previous equation can be expressed in a more compact way with the definition of the catenary constant c:

$$c = \frac{H}{w_c} \tag{10.9}$$

$$y = c \cdot \cosh \frac{x}{c} \tag{10.10}$$

The length of the conductor can be calculated from Equation (10.11) , with a being the span length in meters and h being the altitude difference between the attachment points in meters.

$$L = \sqrt{h^2 + \left[2c \cdot \sinh \frac{a}{2c}\right]^2} \tag{10.11}$$

In order to calculate the distance from the lowest point of the curve *x=0* (see Figure 10.1) to both attachment points, equations (10.12) and (10.13) are used.

$$x_A = c \cdot ln\left[\frac{c}{(L-h)} \cdot (1 - \exp(-a/c))\right] \tag{10.12}$$

$$x_B = x_A + a \tag{10.13}$$

Where:

- x_A is the horizontal distance from the lowest point of the catenary to the first attachment point [m]
- c is the catenary constant [m]
- L is the length of the cable [m]
- h is the height difference between the two attachment points [m]
- a is the span length [m]
- x_B is the horizontal distance from the lowest point of the catenary to the second attachment point [m]

With the previous values of the catenary, the point of maximum sag can be calculated [22] using Equation (10.14) with h being the height difference, a being the span length and x_{min} being the point of lowest altitude, which is equal to 0.

$$x_c = x_{min} + c \cdot arsh\frac{h}{a} \tag{10.14}$$

The sag at any point of the catenary can be calculated using Equation :

$$f = \frac{h \cdot (x - x_A)}{a} + c \cdot \left(\cosh\frac{x_A}{c} - \cosh\frac{x}{c}\right) \tag{10.15}$$

Where:

- f is the sag at point x [m]
- h is the difference in height between the two attachment points [m]
- x is the horizontal distance from the lowest point of the catenary to the point of interest [m]
- x_A is the horizontal distance from the lowest point of the catenary to the first attachment point, calculated from Equation (10.12) [m]
- a is the span length [m]
- c is the catenary constant calculated from Equation (10.9) [m]

10.3.2 Horizontal tension

The most important value that defines the mechanical calculation of a conductor is the horizontal tension, which is the horizontal component of the conductor tensile force. This value plays an important role in defining the catenary of the conductor. In this regard, higher horizontal tensions will result in smaller sags, reducing the height requirements for the support. However, the horizontal tension should be limited to ensure that the rated tensile strength (RTS) of the conductor is not reached, which would lead into a mechanical failure.

According to table 20 of IEC 60826 [18] , the typical range of tensile strength limit is between a 70 % and an 80 % of the RTS. Values higher than that would result in potential damages in the conductors, meaning that the target of the design will be to never surpass a 70% of the conductor's RTS under any meteorological condition. This requirement also affects the design of earth wires.

10.3.3 State change equation

The previous equations for the catenary calculation use a specific value of horizontal tension and mass per unit length of the conductor, but these two values highly depend on the meteorological conditions. Because of this, the catenary has to be calculated for the different hypotheses mentioned in Section 10.2 to ensure a correct design for every condition.

When designing an overhead line for a given hypothesis, the value of the horizontal tension will be defined by that given hypothesis. However, different conditions will result in different values, which could potentially not fit the project's requirements if it was only designed for the initial hypothesis. Because of this, it is important to study the different cases and design the project respecting all of them.

The state change equation is used to translate the horizontal tension obtained under one meteorological condition into a different one. This is used to check that everything is correctly sized and that the line is designed according to the most restrictive condition, never surpassing a certain percentage of horizontal load that could be dangerous to the elements of the line.

The state change equation begins with an initial condition with a specific load per unit length (Q_1), temperature (ϑ_1) and horizontal tension (H_1) which corresponds to the EDS hypothesis mentioned in Section 10.1 .

- $\theta_1 = 15\,°C$
- $Q_1 = Q_{weight}$
- $H_1 = 0.22\,RTS$

From these initial conditions, the horizontal tension H_2 at conditions ϑ_2 and Q_2 can be obtained with the state change Equation (10.16)

$$H_2^2\left[H_2 - H_1 + \frac{\alpha \cdot S \cdot (a_r \cdot Q_1)^2}{24 \cdot H_1^2} + \epsilon \cdot S \cdot (\theta_2 - \theta_1)\right] = \frac{\epsilon \cdot S \cdot \alpha \cdot (a_r \cdot Q_2)^2}{24} \tag{10.16}$$

Where:

- H_2 is the horizontal tension at final conditions [N]
- H_1 is the horizontal tension at initial conditions [N]
- ϵ is the modulus of elasticity of the conductor [Pa]
- α is the coefficient of thermal expansion of the conductor [1/°C]
- S is the conductor's cross section [m^2]
- a_r is the ruling span obtained from Equation (1.1) [m]

- Q_1 is the load per unit length at initial conditions [N/m]
- Q_2 is the load per unit length at final conditions [N/m]
- θ_1 is the temperature at initial conditions [°C]
- θ_2 is the temperature at final conditions [°C]

Previous equation can be rewritten in a simplified version in Equation (10.19), which can be solved using the method proposed in [23]:

$$a = -H_1 + \frac{\epsilon \cdot S \cdot (a_r \cdot Q_1)^2}{24 \cdot H_1^2} + \epsilon \cdot S \cdot \alpha \cdot (\theta_2 - \theta_1) \tag{10.17}$$

$$b = \frac{\alpha \cdot S \cdot (a_r \cdot Q_2)^2}{24} \tag{10.18}$$

$$H_2^2\,[H_2 + a] = b \tag{10.19}$$

If the horizontal tension H_2 gives a value higher than the required 70% RTS, the initial conditions will be changed so that the requirements for the invalid hypothesis are within the limits. For next hypotheses, the reference conditions used will correspond to the updated ones. To better understand this with an example, if the ice hypothesis appears to have a horizontal tension equal to 80%, the reference conditions would have to be changed to the following:

- $\theta_1 = -5°C$
- $Q_1 = Q_{weight} + Q_{ice}$
- $H_1 = 0.7RTS$

These conditions will be used for the rest of the hypotheses until another one does not respect the design values.

After ensuring that the horizontal tensions are correct, the different horizontal tensions under every hypothesis will be calculated using the final state change reference conditions in order to calculate the catenaries using Equation (10.8).

For the earth wire, the horizontal tension will be such that the sag at EDS conditions is not higher than 90% of the sag of the conductor at the same conditions [3]. This will ensure that the clearance between the earth wire and the conductor is respected.

10.4 Tower forces

The forces that the towers of an overhead line withstand are a result of the loads transmitted by the conductors' weight and horizontal tension. The towers of the line will have to withstand vertical, longitudinal and transversal forces for different conditions. This section will present the different hypotheses for the design of the line as well as the calculation model of the forces. The calculation model does not dive deep into the detailed forces in the towers and focuses on the forces at the attachment points of the conductors, not considering the resistances at each part of the tower (in [3] a more detailed calculation is presented). Additionally, the forces of the wind and ice in the towers themselves will not be considered, as they account for a small percentage compared to the ones produced by the conductors.

10.4.1 Tower load hypothesis

In a similar way as with the conductors and earth wires, the loads on the towers will differ depending on the meteorological conditions and the status of the overhead line. Because of this, the following hypotheses have to be studied:

- **Wind:** The conditions of wind speed and temperature are equal to the ones for the conductors, with a 120 km/h wind speed and 10ºC ambient temperature. There is no longitudinal force because the conductors' horizontal tensions are not unbalanced for suspension and angle towers.
- **Heavy load:** The conditions of ice and temperature are equal to the ones used in previous calculations, with an ice density of 900 kg/m^3 , an ice thickness of 30 mm and a temperature of -5ºC. Additionally, a 70% of wind speed will be considered, and similar to the previous hypothesis, no longitudinal force will be applied for suspension and angle towers.
- **Unbalance:** While being under ice load, there is an unbalance in the horizontal tensions of the conductors, resulting in a longitudinal force. A fraction of the horizontal tension under ice conditions will be considered as the longitudinal force depending on the type of tower: For suspension towers 0.15 multiplied by the horizontal tension; for angle towers 0.5; for dead end towers it is not considered because previous hypothesis already studied it.
- **Conductor break:** If a conductor breaks, a severe longitudinal force will appear at the tower's attachment point. This hypothesis considers a line with ice and the following longitudinal forces as a fraction of the conductor's horizontal tension: For suspension towers 0.5 multiplied by the horizontal tension; for angle towers 1; for dead end towers 1.

10.4.2 Vertical forces

When a tower supports a set of conductors and insulators, these elements have a weight that generates a vertical force at the different attachment points of the tower. The calculation of the vertical force can be obtained as a result of adding the conductor's and insulator's weight, as stated in Equation (10.20):

$$F_V = m_c \cdot g \cdot n_{cond} \cdot a_{weight} + n_{ins} \cdot m_{ins} \cdot g \quad (10.20)$$

Where:

- F_V is the vertical force of one attachment point [N]
- m_c is the mass per unit length of the conductor [kg/m]
- n_{cond} is the number of conductors per bundle
- a_{weight} is the weight span of the tower [m]
- n_{ins} is the number of insulators per phase (one string for suspension and dead end towers and two strings for angle towers)
- m_{ins} is the mass of an insulator [kg]

The vertical force on the entire tower can be calculated as the force of one attachment point multiplied by the number of attachment points of the tower (3 per circuit).

10.4.3 Transversal forces

The forces that are applied to the tower sideways are called transversal forces. They are caused be both the wind and the deflection of the conductors. Figure 10.2 shows the transversal forces caused by the conductors in a tower's attachment point.

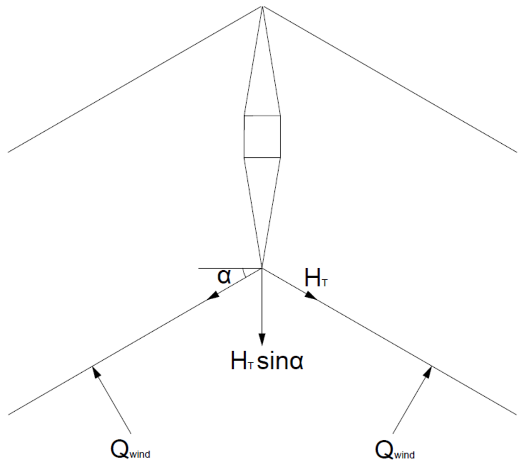

Figure 10.2: Transversal forces of a deflected tower with wind

The force caused by the deflection angle will be defined as the angle resultant, and can be calculated according to Equation (10.21)

$$F_\alpha = (H_{T1} + H_{T2}) \cdot \sin\alpha \tag{10.21}$$

Where:

- F_α is the angle resultant [N]
- α is the deflection angle [rad]
- H_{T1} is the horizontal tension of the previous span [N]
- H_{T2} is the horizontal tension of the next span [N]

Whenever there is wind present, the force that it produces in the conductors will translate into a transversal force in the tower, which can be calculated using Equation (10.22)

$$F_{wind} = Q_{wind} \cdot a_{wind} \cdot \cos\alpha \cdot n_{cond} \tag{10.22}$$

Where:

- F_{wind} is the transversal force caused by the wind on a conductor bundle [N]
- Q_{wind} is the wind load per unit length of the conductor [N/m]
- a_{wind} is the wind span of the tower [m]
- α is the deflection angle [rad]
- n_{cond} is the number of conductors in the bundle

The total transversal force at the tower will therefore be calculated according to Equation (10.23):

$$F_T = F_\alpha + F_{wind} \tag{10.23}$$

The forces calculated with Equations (10.21) and (10.22) define the transversal forces at one attachment point of the tower, consequently in order to calculate the entire transversal forces of the tower, the values must be multiplied by the number of phases of the tower.

10.4.4 Longitudinal forces

The calculation of the longitudinal forces depends primarily on the percentage of the horizontal tension that is considered for the different hypotheses. Additionally, the deflection angle of the tower also defines the longitudinal loads that the conductors tension generates.

The expression used to calculate the longitudinal forces of a conductor bundle is the following:

$$F_L = \delta \cdot H \cdot n_{cond} \cdot \cos\alpha \tag{10.24}$$

Where:

- F_L is the longitudinal force of a conductor bundle [N]
- δ is the fraction of the horizontal tension that will be considered as longitudinal force
- H is the maximum horizontal tension between the previous and next span's conductor [N]
- n_{cond} is the number of conductors in the bundle
- α is the deflection angle [rad]

Similarly to the vertical and transversal calculation, the longitudinal forces refer to a single phase. However, in this case, some of the hypotheses might not take into account the longitudinal force of all of the conductors, therefore this force is only multiplied by the number of phases for dead end towers.

Chapter 11

Tower spotting

Another important parameter in the investment of an overhead line is the placement of the towers within the line. Spotting the towers in a way or another impacts directly the cost of the line. By way of explanation, tower spotting must consider the clearances, the catenary and all the other elements that define the line.

In this chapter the tower's spotting criteria and process will be explained.

11.1 Considerations

In this methodology, a line with the least number of angle towers is prioritized, according to [3] an overhead line route which avoids angle towers is favored to be selected. Hence, the angle towers uploaded by the users are preserved and no other angle tower is added in the spotting process. If a user imports close angle towers that do not respect the minimum allowable span, the towers are kept and a warning is displayed in the results.

Furthermore, a target span calculated based on the line voltage is considered to ensure a tolerated span length, the target span is calculated as seen in Table 2.1. Moreover, the elevation data under the entire line is considered for placing new suspension towers within the blocks; the terrain data consideration is necessary to ensure the minimum clearance to the ground criteria.

Before jumping into the spotting process, the line imported by the users goes through a filter based on the angle towers criteria mentioned above. The angle towers are considered when there is a deflection angle higher than 2° or less than -2°; these towers are kept and the rest of points/towers are removed.

11.2 Spotting process

The spotting process in this methodology follows three different steps; the first step is called a distance check where the algorithm ensures that the users blocks respect the allowable distances and distributes suspension towers depending on the target spans. In the second step, the ground clearance distance in each span is validated and new possible towers based on the elevation data are considered. Finally, in the last step, the new towers are spotted with a final check.

This process is repeated in a way that the final route respects the minimum ground clearance and the span length while including the necessary towers only to evacuate the power.

11.2.1 Distance check

In the distance check step, the blocks lengths are evaluated to make sure there is enough space between all the angle towers; this evaluation considers a tolerance span of 40% of the target span which a block's length can tolerate.

In addition, in this step, the suspension towers are located within the blocks based on a maximum span calculated from the target span defined by the system voltage. The maximum span is calculated as the target span multiplied by 1.15 to allow up to 15% bigger spans. For every block imported by the user, its corresponding elevation data is calculated; hence, for every maximum span the corresponding point is retrieved and considered as a new possible tower.

Later, the possible new towers are added to the line in a way that guarantees all the distances between the towers respect the target spans, if not, a consideration of new possible towers is made. Also, new elevation data is defined based on the new spans of the line.

In the Figure 11.1 an illustration of a plan view of a line imported by the user is presented; the distance check criteria are also shown.

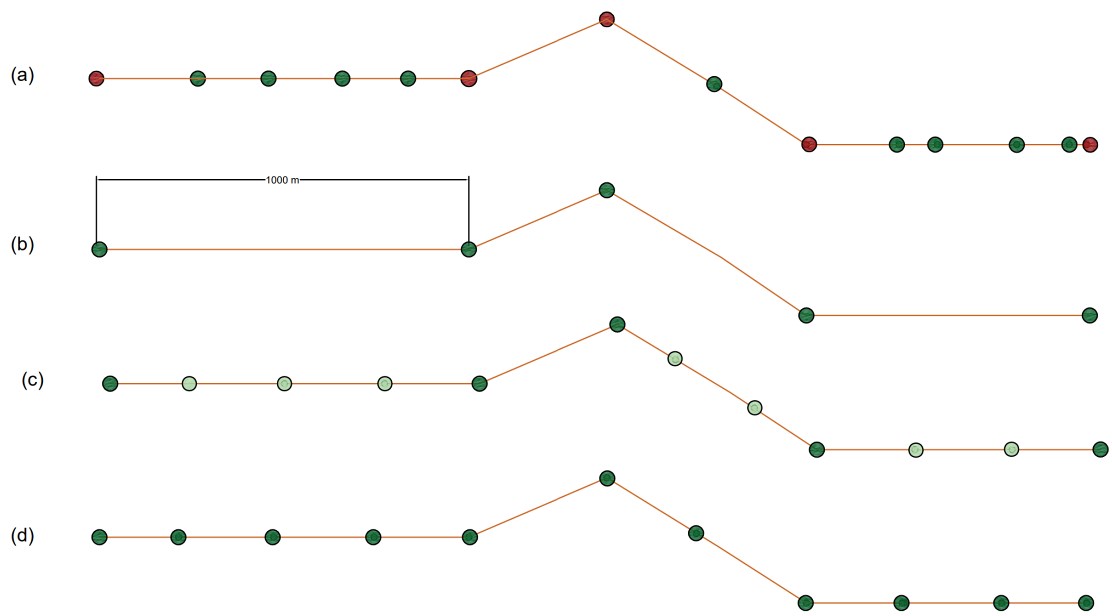

Figure 11.1: The distance check: (a) User line path | (b) Path filtering | (c) Possible towers location | (d) Suspension towers are added

11.2.2 Ground clearance validation

In order to have a valid path one of the most important criteria is for the towers to be placed in such a way that the spans' catenaries respect the minimum ground clearance. To guarantee this criteria, a ground clearance validation is run on the line composed of the towers from the distance check step.

The process of ground clearance validation includes the calculation of the catenaries of the line considered from the previous step; afterwards, the maximum height of the tower' body is calculated based on the voltage of the system as presented in Table 11.1 which was elaborated based on market towers catalog [19]. The maximum height is used to define the lowest connection point of the towers depending on their type to recalculate the correct catenary of the conductors.

For every two consecutive spans, the minimum ground clearance is validated against the spans' elevation data. For every span where the ground clearance is not respected, its corresponding towers are defined as invalid, the ground clearance validation procedure allows keeping track of all the spans and towers where the clearance is not respected for it to be used to find possible valid towers in the following step.

Table 11.1: The maximum tower height. Source: Imedexsa [19]

Maximum voltage U [kV]	Maximum tower height [m]	Tower name
⩽66	30.22	Milano
⩽132	33.05	Halcon Real
⩽220	39.2	Condor
>220	40	Gran Condor/Icaro

In the Figure 11.2 below, an illustration of ground clearance validation of a line composed of three spans is shown, the towers in red are the invalidated towers because of the invalid first span that do not respect the ground clearance, the other spans are respecting the criteria; hence, represented by a green color.

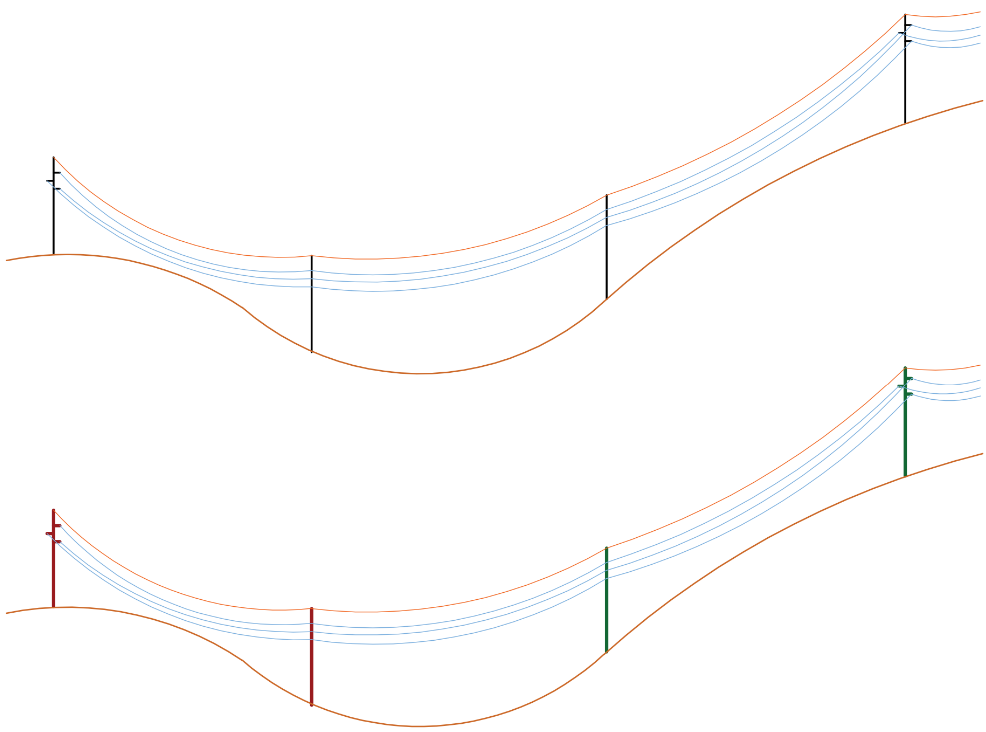

Figure 11.2: The ground clearance validation

11.2.3 Valid towers spotting

Finally, in this last step of tower spotting, the invalid spans are evaluated depending on the type of the tower that compose them. The evaluation results in adding new suspension towers and creating new spans when needed.

In one hand, when the invalid span is made of two angle towers, a new tower is added at the middle of the span to correct the ground clearance. On the other hand, if the span contains at least one suspension tower, the adjacent spans must be evaluated. Based on the validity or invalidity of the adjacent spans, the towers are moved forward or backward to make sure the spans respect the minimum ground clearance criteria. The movement of the possible valid towers considers the minimum allowable span required.

The new positions of the moved towers are selected in a way that high ground positions are prioritized while trying to keep the towers as equally spaced as possible. Once the new towers positions are defined, the previous step is run again to make sure the correct spans are respecting the minimum ground clearance.

In the case of not being able to find a tower's position that would validate a certain span, adding an extra tower is considered. In the following Figure 11.3 an illustration of a tower path made of three spans with the first span being invalid.

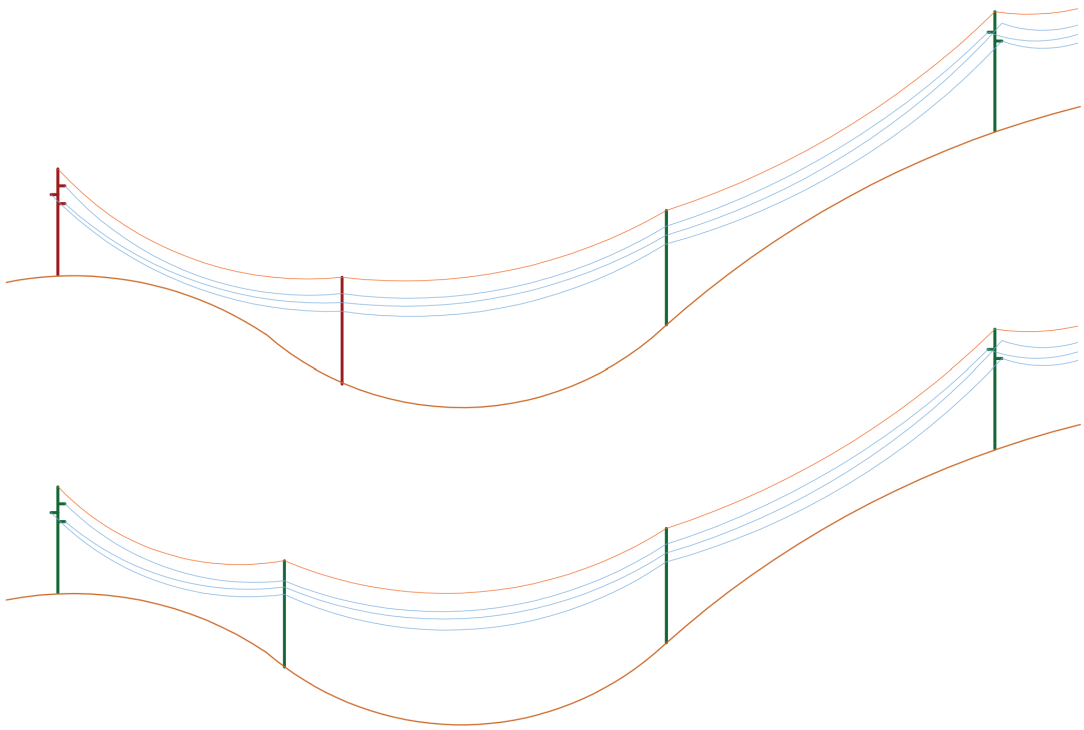

Figure 11.3: Tower spotting sample

Bibliography

[1] Grigsby, L.L., *The Electric Power Engineering Handbook - Five Volume Set (3rd ed.)* Taylor and Francis, 2012.

[2] Félix Ignacio Pérez Cicala, Mario Bennekers Vallejo and Miguel Ángel Torrero Rionegro, "Topography analysis methodology (2022 edition)," RatedPower, 2017.

[3] F. Kiessling, P. Nefzger, J. F. Nolasco, and U. Kaintzyk, *Overhead Power Lines: Planning Design Construction.* Springer, 2003.

[4] Technical Committee 7, "Overhead electrical conductors – Calculation methods for stranded bare conductors," International Electrotechnical Commision, Tech. Rep. IEC 61597, 2012.

[5] Siemens AG, "Power Engineering Guide Edition 8.0," Siemens, Tech. Rep., 2017.

[6] "Aerial optical cables along electrical power lines," ZTT, catalog, 2007.

[7] Technical Committee 14, "Power transformers - part 5: Ability to withstand short circuit," International Electrotechnical Commision, Tech. Rep. IEC 60076-5:2006, 2006.

[8] Viesgo, "Norma instalaciones de enlace en alta tension: lineas de alta tension (>36 kV) y subestaciones," Viesgo, Technical Specification NT-IEAT.01, 2017.

[9] Viesgo, "Proyecto tpo de subestacionesc con aparamenta convencional," Viesgo, Technical Specification PT-SECO.01, 2017.

[10] J. P. Fernandez and E. Iraburu, "Especificaciones Particulares. Requisitos Tecnicos de Construccion de Subestaciones conectadas a redes de Alta Tension de Un > 36 kV," Union Fenosa Distribucion, Technical Specification IT.07974.ES-DE.NOR, 2017.

[11] Technical Committee 99, "Insulation coordination. Part 2. Application guidelines," International Electrotechnical Commision, Tech. Rep. IEC 60071-2:2018, 2018.

[12] Ignacio Álvarez Iberlucea, Soukayna Jermouni, Miguel Ángel Torrero Rionegro, Félix Ignacio Pérez Cicala and Juan Romero González, "Substation methodology (2020 edition)," RatedPower, 2020.

[13] Technical Committee 36, "Insulators for overhead lines with a nominal voltage above 1000 V - Ceramic or glass insulator units for AC systems - Characteristics of insulator units of the cap and pin type," International Electromechanical Commision, Tech. Rep. IEC 60305:2021, 2021.

[14] Technical Committee 36, "Insulators for overhead lines with a nominal voltage above 1000 V - Ceramic insulators for AC systems - Characteristics of insulator units of the long rod type," International Electromechanical Commision, Tech. Rep. IEC 60433:2021, 2021.

[15] ABB, *Switchgear Manual*, 11th ed. 2007.

[16] Technical Committee 36, "Selection and dimensioning of high-voltage insulators intended for use in polluted conditions - Part 1: Definitions, information and general principles," International Electrotechnical Commision, Tech. Rep. IEC 60815-1:2008, 2008.

[17] European Committee for Electrotechnical Standardization, "Overhead electrical lines exceeding AC 1 kV - Part 1: General requirements - Common specifications," CENELEC, Tech. Rep. EN 50341-1, 2012.

[18] Technical Committee 11, "Overhead transmission lines - design criteria," International Electrotechnical Commission, Tech. Rep. IEC 60826:2017, 2017.

[19] "Catalogo general," Imedexsa, catalog, 2012.

[20] F.W. Peek, "The law of corona and dielectric strength of air," 1912.

[21] "Conductor safe design tension with respect to aeolian vibrations," CIGRE, Tech. Rep. CIGRE Report 273, 2005.

[22] A. Hatibovic, "Derivation of equations for conductor and sag curves of an overhead line based on a given catenary constant," 2013.

[23] S.Partheepan and D.Sivalingam, "Solution to cubic equation using java programming," 2020.

Appendix A

Selecting a phase conductor and an insulator

In this appendix, the process and calculation of the phase conductor cross-section as well as the selection of the line insulator will be presented.

The overhead line to be designed is a transmission line evacuating a capacity of 100MW for a high voltage level of 132kV and frequency of 50Hz. The system is simplex with one circuit and one conductor per phase.

A.1 Selection of the phase conductor

As explained in Chapter 2, the selection of the conductor depends mainly on the thermal limit criteria and the mechanical criterion.

The line is of a transmission nature; hence, the conductors to select from are of type ACSR. In this example, the conductor used for the selection is the "160-A1/S2A" with a total diameter of 0.0177 m and a unitary mass of 0.64459 kg/m.

The thermal limit withstand is checked by calculating the conductor maximum admissible current using Equation (2.3) and comparing it with the total current of the line calculated as:

$$I_{tot} = \frac{S}{U_{max} \cdot n \cdot \sqrt{3}} = \frac{100 \cdot 10^6}{132000 \cdot 1 \cdot \sqrt{3}} \approx 437A \quad \text{(A.1)}$$

To calculate the maximum admissible current, first, the DC resistance at maximum temperature must be calculated:

$$R_T = \frac{\rho}{s}[1 + \alpha(T_{max} - 20)] = \frac{3.35 \cdot 10^{-8}}{1.8622 \cdot 10^{-4}}[1 + (0.00403(80 - 20))] \approx 2.234 \cdot 10^{-4} W/m \quad \text{(A.2)}$$

Next, the heat loss by radiation, the convection loss and the solar heat gain must be calculated respectively:

$$N_R = k \cdot \pi \cdot d \cdot K_e({T_{max}}^4 - {T_{am}}^4) = 5.67 \cdot 10^{-8} \cdot \pi \cdot 0.0177 \cdot 0.45(353^4 - 318^4) \approx 7.52W/m \quad (A.3)$$

$$N_C = \lambda \cdot Nu \cdot \pi \cdot (T_{max} - T_{am}) = 0.02585 \cdot 25.7 \cdot \pi \cdot (353 - 318) \approx 73.1W/m \quad (A.4)$$

$$N_S = Y \cdot d \cdot S_i = 0.0177 \cdot 1045 \cdot 0.8 \approx 14.8W/m \quad (A.5)$$

Hence, the maximum admissible current of the conductor is:

$$I_{max} = \sqrt{\frac{N_R + N_C - N_S}{R_T}} \cdot n = \sqrt{\frac{7.52 + 73.1 - 14.8}{2.234 \cdot 10^{-4}}} \cdot 1 \approx 543A \quad (A.6)$$

Since the conductor admissible current is higher than the total current of the line, the conductor "160-A1/S2A" is electrically eligible.

Next, the mechanical withstand is checked for the conductor using the empirical approach explained in section 2.2.2. For the high voltage of 132kV, the maximum target span is 200 m (Table 2.1). Hence, from Table 2.2 it is deducted that the minimum tensile strength is 45000 N .

On the other hand, the electrical eligible conductor has a maximum load of 61340 N. Consequently, the conductor withstands mechanically.

The final step in the conductor selection is checking the voltage gradient criterion, as mentioned in the Chapter 2 using Equation (A.7) and ensuring that the line's voltage drop and power losses are not exceeding 5%. In Appendix B, both, the voltage drop and total losses are calculated for this line's design and both do not exceed the 5% criterion. The voltage gradient is calculated as follows:

$$\begin{aligned} E_i = & \frac{C_i}{2\pi\epsilon_0 \cdot n_2 \cdot r}[1 + 2 \cdot (r/s)(n_2 - 1) \cdot sin(\pi/n_2)]\frac{U}{\sqrt{3} \cdot 100} = \\ & \frac{8.23 \cdot 10^{-12}}{2 \cdot \pi \cdot 8.854 \cdot 10^{-12} \cdot 1 \cdot 0.00885} \\ & [1 + 2 \cdot (0.00885/0.4)(1 - 1) \cdot sin(\pi/1)]\frac{132000}{\sqrt{3} \cdot 10^4} \approx 12.7kV/cm \end{aligned} \quad (A.7)$$

As the voltage gradient is less than the maximum 17kV/cm, the conductor "160-A1/S2A" complies with the selection criteria; hence, it is the conductor of the this transmission line.

A.2 Selection of the insulator

To select the correct insulator for suspension and tension following this methodology, electrical and mechanical criteria are considered.

For the same transmission line with the conductor "160-A1/S2A" having a maximum load of 61340 N, the insulator selection will depend, first, on the electrical withstand of the cap and pin insulator. The insulator "U160BS" is chosen as an example of insulator selection. To assess the electrical withstand, the length of the insulator is calculated under different conditions to ensure it respects the electrical clearances and to guarantee the insulator withstands the maximum voltage.

- Normal conditions:

$$n_{normal} \geq \frac{U_s \cdot \epsilon_0}{\epsilon} = \frac{145000 \cdot 20 \cdot 10^{-6}}{0.315} = 9.21 \tag{A.8}$$

- Wet and lightning impulse conditions:

For both conditions, the number of disks that withstand the maximum wet voltage and the lightning impulse voltage is seven.

Hence, for the three conditions the longest insulator is composed of 10 pins, which is the integer immediately superior to 9.21; and for a phase to earth clearance of 1.2m, the insulator minimum length is calculated as:

$$L_{ins} = d_{pp} \cdot 1.1 = 1.2 \cdot 1.1 = 1.32m \tag{A.9}$$

Since the insulator total length $(10 \cdot 0.146 = 1.46)$ is higher than the minimum length, then the insulator is electrically compliant.

Next, the minimum failing load of the insulator must be checked against the conductor maximum load at worst conditions. The different combinations of insulators sets are also assessed. As the minimum failing load is 160000 N and higher than the conductor maximum load, the insulator "U160BS" withstands mechanically.

Finally, as explained in the chapter, the typical tensile strength for insulators under the voltage of 132kV is 160000 N Table 6.3 which is equal to the insulator "U160BS" minimum failing load. Hence, the said insulator is selected.

Appendix B

Electrical parameters calculation

In this appendix, the process and calculation of the electrical calculations of an overhead line are presented.

The overhead line in question has the same characteristics mentioned in Appendix A. The line operating under a voltage of 132kV has a length of 8955m and a power factor at the sending end of 0.95. As explained in Chapter 9, the distributed parameters model will be considered for the electrical calculation.

B.1 Resistance

The resistance of the line per unit length is calculated using Equation (9.28) as follows:

$$R = \frac{R_{AC}}{n_c \cdot n_s} \cdot L = \frac{2.24 \cdot 10^{-4}}{1 \cdot 1} \cdot 8955 \approx 2\Omega/m \tag{B.1}$$

B.2 Inductance and reactance

To calculate the inductance of the line, the GMD and GMR must be calculated. An accurate GMD is calculated using Equation (9.16)

$$\overline{GMD}_{ohl} = \frac{\sum_{i=1}^{spans} \left(\overline{GMD}_i \cdot L_i\right)}{L_{ohl}} \approx 7.9m \tag{B.2}$$

As for GMR, it is calculated using Equation (9.18):

$$GMR = \sqrt[n]{r' \cdot \prod_{i=2}^{n} d_{1\rightarrow i}} \approx 0.0069m \tag{B.3}$$

Next, as the transmission line is Simplex with one circuit, the inductance of the line is calculated using the following formula:

$$L = \frac{\mu_0}{2\pi} \cdot \ln \frac{GMD}{GMR} \cdot l = \frac{1.256 \cdot 10^{-6}}{2\pi} \cdot \ln \frac{7.9}{0.0069} \cdot 8955 \approx 0.0126 H/m \quad \text{(B.4)}$$

Finally, the inductive reactance can be deduced from Equation (9.33) as follows:

$$X_L = 2\pi \cdot f \cdot L = 2\pi \cdot 50 \cdot 0.0126 \approx 3.97\Omega \quad \text{(B.5)}$$

B.3 Impedance

Having the resistance and the inductive reactance of the line calculated in the previous sections, the impedance of the entire line can be calculated using Equation (9.34):

$$\vec{Z} = R + jX_L = 2 + j3.97 = 4.44\Omega \quad \text{(B.6)}$$

B.4 Capacitance and susceptance

The capacitance of a simplex line can be calculated following the Equation (9.35):

$$C = \frac{2\pi\epsilon_0}{\ln\left(\frac{GMD}{GMR_C \cdot \sqrt{1+(GMD/2h_M)^2}}\right)} \cdot l = \frac{2\pi \cdot 8.854 \cdot 10^{-12}}{\ln\left(\frac{7.9}{0.00885 \cdot \sqrt{1+(7.9/2 \cdot 14.7)^2}}\right)} \cdot 8955 \approx 7.37 \cdot 10^{-8} F/m \quad \text{(B.7)}$$

Once the capacitance is calculated, the capacitive reactance and the susceptance are calculated as follows:

$$X_C = \frac{1}{2\pi \cdot f \cdot C} = \frac{1}{2\pi \cdot 50 \cdot 7.37 \cdot 10^{-8}} \approx 43203.7\Omega/m \quad \text{(B.8)}$$

$$B = 2\pi \cdot f \cdot C = 2\pi \cdot 50 \cdot 7.37 \cdot 10^{-8} \approx 2.32 \cdot 10^{-5}\Omega^{-1}m^{-1} \quad \text{(B.9)}$$

B.5 Voltage drop

To calculate the voltage drop using the distributed parameters electrical model, first, the voltage at the receiving end must be identified. This latter is calculated using Equation (9.7):

$$\begin{aligned} V = & V_s \cdot \cosh\gamma - I_s \cdot Z_0 \cdot \sinh\gamma = \\ & (76210.2 + j0) \cdot (0.99 + j2.32 \cdot 10^{-5}) - (415.5 - j136.57) \cdot \\ & (426.17 - j101.58) \cdot (0.00235 + j0.00986) = (74832.5 - j1372.03) \end{aligned} \quad \text{(B.10)}$$

Consequently, the voltage drop and its percent are calculated as follows:

$$\Delta V = |V_s| - |V_r| \approx 2364.5V \quad \text{(B.11)}$$

$$\Delta V(\%) = \frac{|V_s| - |V_r|}{|V_s|} \cdot 100 = \frac{2364.5}{132000} \cdot 100 \approx 1.8\% \tag{B.12}$$

B.6 Joule losses

The joule effect loss is the difference between the power loss at the sending loss and that of the end of the line. To calculate the power losses, the current at receiving end must be calculated using Equation (9.8):

$$\begin{aligned} I =& (415.5 - j136.57) \cdot (0.99 + j2.32 \cdot 10^{-5}) - \\ & \frac{(76210.2 + j0)}{(426.17 - j101.58)} \cdot (0.00235 + j0.00986) = (415.5 - j138.3) \end{aligned} \tag{B.13}$$

Next, with the receiving end power factor being 0.9544, both the power losses at sending and receiving ends are calculated as follows:

$$P_s = V_s \cdot I_s \cdot \sqrt{3} \cdot \cos\phi_s = 132000 \cdot 437.38 \cdot \sqrt{3} \cdot 0.95 \approx 9.5 \cdot 10^7 W \tag{B.14}$$

$$P_r = V_r \cdot I_r \cdot \sqrt{3} \cdot \cos\phi_r = 74845.06 \cdot 437.92 \cdot \sqrt{3} \cdot 0.9544 \approx 9.4 \cdot 10^7 W \tag{B.15}$$

Finally, the joule effect and its percent are calculated using Equation (9.46) and Equation (9.47):

$$\Delta P = P_r - P_s \approx 1151654W \tag{B.16}$$

$$\Delta P(\%) = \frac{P_r - P_s}{P_s} \cdot 100 \approx 1.2\% \tag{B.17}$$

B.7 Corona losses

In case of the occurrence of the Corona effect, its corresponding loss is calculated; to know the if the effect occur, the critical disruptive voltage is calculated first using Equation (9.48):

$$V_p = \frac{29.8}{\sqrt{2}} \cdot m_c \cdot \delta \cdot m_t \cdot r \cdot n \cdot \ln\frac{GMD}{r} = \frac{29.8}{\sqrt{2}} \cdot 0.85 \cdot 0.96553 \cdot 0.8 \cdot 0.885 \cdot 1 \cdot \ln\frac{0.00885}{0.885} \approx 144139.4V \tag{B.18}$$

As the maximum voltage of the line 145kV is higher than the disruptive voltage, the corona effect will occur and its loss is calculated as follows:

$$\begin{aligned} P_{Corona} &= \frac{241}{\delta} \cdot (f + 25) \cdot \sqrt{\frac{r}{GMD}} \cdot \left(\frac{V_{max} - V_{Cmax}}{\sqrt{3}}\right)^2 \cdot 10^{-5} \\ &= \frac{241}{0.96553} \cdot (50 + 25) \cdot \sqrt{\frac{0.885}{792.03}} \cdot \left(\frac{145000 - 144139.4}{\sqrt{3}}\right)^2 \cdot 10^{-5} \approx 0.0016W \end{aligned} \tag{B.19}$$

The corona loss is then multiplied by the total number of phases, the number of sub-conductors and the length of the line to get the corona loss of the line resulting in this case a loss of 41.5W.

Finally, the total losses percentage is:

$$P_{tot\%} = \frac{\Delta P + P_{Corona}}{S} 100 = \frac{1151654 + 41.5}{100000} 100 \approx 1.15\% \tag{B.20}$$

Appendix C

Mechanical calculations

This appendix presents the different mechanical calculations performed for the design of an overhead line. The appendix will cover the conductor's loads and the catenary of a span under different hypotheses as well as the tower forces of a suspension and a tension tower.

C.1 Calculation of the loads

For the different hypotheses mentioned in Section 10.2, the loads per unit length of the conductor can be calculated. The conductor's characteristics necessary for the mechanical calculation are presented in Table C.1:

Table C.1: Mechanical data of the conductor "160-A1/S2A"

Diameter [m]	Unitary Mass [kg/m]	Tensile Strength [N]	Section [m^2]	Elasticity [Pa]	Thermal Expansion [1/°C]
0.0177	0.6449	61340	$1.862 \cdot 10^{-4}$	$7.454 \cdot 10^{10}$	$1.887 \cdot 10^{-5}$

The weight load per unit length can be calculated from (10.1):

$$Q_{weight} = m_c \cdot g = 0.6449 \cdot 9.81 = 6.326\, N/m \tag{C.1}$$

The wind pressure is obtained from (10.2):

$$q_{max} = \frac{1}{2}\tau\mu \left(V_{max}\right)^2 = \frac{1}{2} \cdot 1 \cdot 1.225 \cdot 33.33^2 = 680.42\, N/m^2 \tag{C.2}$$

$$q_{75\%} = \frac{1}{2}\tau\mu \left(V_{75\%}\right)^2 = \frac{1}{2} \cdot 1 \cdot 1.225 * (0.75 * 33.33)^2 = 382.74\, N/m^2 \tag{C.3}$$

The wind load per unit length is therefore calculated using (10.3):

$$Q_{wind,max} = q_{max} \cdot C_{xc} \cdot G_c \cdot G_L \cdot d \cdot \sin^2 \Omega = 680.42 \cdot 1 \cdot 1 \cdot 0.0177 \cdot \sin^2 90 = 12.04\, N/m \tag{C.4}$$

$$Q_{wind,75\%} = q_{75\%} \cdot C_{xc} \cdot G_c \cdot G_L \cdot d \cdot \sin^2 \Omega = 382.74 \cdot 1 \cdot 1 \cdot 0.0177 \cdot \sin^2 90 = 6.77\, N/m \tag{C.5}$$

The ice load per unit length is obtained from (10.6):

$$Q_{ice} = 9.82 \cdot 10^{-3} \cdot \delta \cdot \pi \cdot t \cdot (d + t/1000) = \\ 9.82 \cdot 10^{-3} \cdot 900 \cdot \pi \cdot 30 \cdot (0.0177 + 30/1000) = 39.73\,N/m \tag{C.6}$$

C.2 Maximum horizontal tension

Once the loads per unit length have been obtained for the different meteorological conditions, the horizontal tensions can be calculated so that their value does not surpass a threshold under any of the hypotheses.

For this, the state change equation must be used in order to compare the tensions of the different hypotheses. None of the conditions should reach a horizontal tension higher than 70% of the conductor's RTS:

$$H_{max} < 0.7 \cdot 61340 = 42938\,N \tag{C.7}$$

The initial conditions for this calculation will be EDS conditions with a horizontal tension equal to 22% of the conductor's tensile strength:

- $\theta_1 = 15\,°C$
- $Q_1 = Q_{weight} = 6.326\,N/m$
- $H_1 = 0.22 \cdot 61340 = 13494.8\,N$

The first hypothesis to study will be the max wind one, with the following final conditions:

- $\theta_2 = 10\,°C$
- $Q_2 = \sqrt{6.326^2 + 12.04^2} = 13.6\,N/m$

From equations (10.17), (10.18) and (10.19)

$$a = -13494.8 + \frac{7.454 \cdot 10^{10} \cdot 1.862 \cdot 10^{-4} \cdot (211.85 \cdot 6.326)^2}{24 \cdot 13494.8^2} \\ + 7.454 \cdot 10^{10} \cdot 1.887 \cdot 10^{-5} \cdot 1.862 \cdot 10^{-4} \cdot (10 - 15) = -9100.8\,N \tag{C.8}$$

$$b = \frac{7.454 \cdot 10^{10} \cdot 1.862 \cdot 10^{-4} \cdot (211.85 \cdot 13.6)}{24} = 4.8 \cdot 10^{12}\,N^3 \tag{C.9}$$

$$H_2^2[H_2 + (-9100.8)] = 4.8 \cdot 10^{12} \tag{C.10}$$

Solving previous equation, the value of H_2 obtained is $H_2 = 20510.7\,N$, which is lower than the maximum allowed of 42938 N, meaning that the wind conditions are correct.

The second hypothesis will be the ice conditions hypothesis, with the final conditions:

- $\theta_2 = -5\,°C$
- $Q_2 = 6.326 + 39.73 = 46.056\,N/m$

The values for a, b and H_2 are:

$$a = -13494.8 + \frac{7.454 \cdot 10^{10} \cdot 1.862 \cdot 10^{-4} \cdot (211.85 \cdot 6.326)^2}{24 \cdot 13494.8^2} + 7.454 \cdot 10^{10} \cdot 1.887 \cdot 10^{-5} \cdot 1.862 \cdot 10^{-4} \cdot (-5 - 15) = -13029.38\,N \quad (C.11)$$

$$b = \frac{7.454 \cdot 10^{10} \cdot 1.862 \cdot 10^{-4} \cdot (211.85 \cdot 46.056)^2}{24} = 5.5 \cdot 10^{13}\,N^3 \quad (C.12)$$

$$H_2 = 42905.86\,N \quad (C.13)$$

Since the value of H_2 is lower than the 42938 N limit, the ice hypothesis is correct.

The third hypothesis to study is the combined loads one, with the following final conditions:

- $\theta_2 = -5\,°C$
- $Q_2 = \sqrt{(6.326 + 39.73)^2 + 6.77^2} = 46.551\,N/m$

The values for a, b and H_2 are:

$$a = -13494.8 + \frac{7.454 \cdot 10^{10} \cdot 1.862 \cdot 10^{-4} \cdot (211.85 \cdot 6.326)^2}{24 \cdot 13494.8^2} + 7.454 \cdot 10^{10} \cdot 1.887 \cdot 10^{-5} \cdot 1.862 \cdot 10^{-4} \cdot (-5 - 15) = -13029.38\,N \quad (C.14)$$

$$b = \frac{7.454 \cdot 10^{10} \cdot 1.862 \cdot 10^{-4} \cdot (211.85 \cdot 46.551)^2}{24} = 5.62 \cdot 10^{13}\,N^3 \quad (C.15)$$

$$H_2 = 43176.37\,N \quad (C.16)$$

In this case, the horizontal tension for the heavy load hypothesis is higher than the maximum horizontal tension allowed. This means that the horizontal tension should be lowered so that, under heavy load conditions, the horizontal tension is within the safety limits of the conductor. Therefore, the initial conditions are changed to the following:

- $\theta_1 = -5\,°C$
- $Q_1 = 46.551\,N/m$
- $H_1 = 42938\,N$

These conditions will make sure that the heavy load hypothesis is respected while ensuring that the previously studied hypotheses are also respected since the horizontal tension will be lower with the new conditions (lowering the tension under one hypothesis will lower it for the rest of them).

The maximum temperature hypothesis is not taken into account when trying to study if the horizontal tension is respected, since this hypothesis will yield really low values of H_2.

C.3 Horizontal tension calculation

In the previous section, the most unfavorable initial conditions were established after studying the different hypotheses, showing that the worst condition for this block is the one corresponding to the heavy loads hypothesis.

Because the initial conditions were changed, the values for the horizontal tensions calculated previous to the heavy loads hypothesis will have changed, meaning that they have to be recalculated with the new initial conditions.

In order not to repeat all the calculations, the final horizontal tensions with the new conditions are obtained following the previous procedure with the heavy load's conditions as the initial conditions. The results are shown in Table C.2.

C.4 Catenary calculation

After obtaining the horizontal tensions, the catenary curve can be calculated for every hypothesis (details in Section 10.3). The example calculation will be done for the heavy loads hypothesis with the following values:

- $H = 42938N$
- $A = \{0,\ 0,\ 0\}$, coordinates in meters
- $B = \{245.4,\ 2.3,\ -4.4\}$, coordinates in meters
- $m_c = 46.056\, N/m$, considering the weight of the conductor and the ice

The span length can be calculated as:

$$a = \sqrt{(B.x - A.x)^2\ (B.y - A.y)^2} = \sqrt{(245.4 - 0)^2\ (2.3 - 0)^2} = 245.41\, m \tag{C.17}$$

The difference in altitudes is calculated from:

$$h = B.z - A.z = -4.4 - 0 = -4.4\, m \tag{C.18}$$

The catenary constant c is calculated from Equation (10.9):

$$c = \frac{H}{w_c} = \frac{42938}{46.056} = 932.3\, m \tag{C.19}$$

The length of the curve is obtained from Equation (10.11):

$$L = \sqrt{h^2 + \left[2c \cdot \sinh\frac{a}{2c}\right]^2} = \sqrt{(-4.4)^2 + \left[2 \cdot 932.3 \cdot \sinh\frac{245.41}{2 \cdot 932.3}\right]^2} = 246.16\, m \tag{C.20}$$

The distance x_A is then calculated according to (10.12):

$$\begin{aligned} x_A =& c \cdot ln\left[\frac{H}{w_c \cdot (L-h)} \cdot (1 - \exp(-a/c))\right] = \\ & 932.3 \cdot ln\left[\frac{42938}{46.056 \cdot (246.16 - (-4.4))} \cdot \left(1 - \exp\left(\frac{-245.41}{932.3}\right)\right)\right] = -139.38\, m \end{aligned} \tag{C.21}$$

$$x_B = x_A + a = -139.38 + 245.41 = 106.03\, m \tag{C.22}$$

The point where the maximum sag appears is calculated from Equation (10.14)

$$x_c = x_{min} + c \cdot arsh\frac{h}{a} = 0 + 932.3 \cdot arsh\frac{-4.4}{245.41} = -16.61\, m \tag{C.23}$$

The max sag is therefore:

$$\begin{aligned} f =& \frac{h \cdot (x_c - x_A)}{a} + c \cdot \left(\cosh\frac{x_A}{c} - \cosh\frac{x_c}{c}\right) = \\ & \frac{-4.4 \cdot (-16.61 + 139.38)}{245.41} + 932.3 \cdot \left(\cosh\frac{-139.38}{932.3} - \cosh\frac{-16.61}{932.3}\right) = 8.089\, m \end{aligned} \tag{C.24}$$

All of the catenaries for the different hypotheses will be calculated for every span. By doing this, the worst case scenarios for both, horizontal tension and clearances will be studied, providing a good quality design.

The result for the different hypotheses are shown in Table C.2:

Table C.2: Sags and tensions

Hypothesis	Temperature [°C]	Loads [N/m]	Hor. tension [N]	Hor. tension [%]	Max Sag [m]
Max Temp.	85	6.326	7469	12.17	6.38
EDS	15	6.326	13172	21.47	3.62
Wind Loads	10	13.600	20216	32.96	2.36
Ice Loads	-5	46.056	42670	69.56	8.14
Heavy Loads	-5	46.551	42938	70.00	8.09

C.5 Tower forces

The calculation of the forces in the towers will be performed considering one suspension tower and one angle tower with one conductor per phase bundle and one circuit.

Table C.3: Inputs for tower forces calculation

Tower	Wind Span [m]	Hypothesis	Weight Span [m]	Conductor Weight [N/m]	Hor. tension [N]
Suspension	216.0	Max wind	690.8	6.326	20216
		Heavy load	353.7	46.056	42938
		Unbalance	352.9	46.056	42670
		Cond. break	352.9	46.056	42670
Angle	216.8	Max wind	443.9	6.326	18391
		Heavy load	279.66	46.056	42938
		Unbalance	279.3	46.056	42645
		Cond. break	279.3	46.056	42645

Some additional data necessary for the calculation is presented:

- $w_{ins} = 608.22\,N$, which is the weight of the insulator
- n_{ins}, which is the number of insulators per bundle, takes a value of 1 for the suspension tower and 2 for the angle tower
- $\alpha_{angle} = 3.27°$, which is the deflection angle of the angle tower. This has to be divided by two, since it takes into account the sum of the angle with both spans of the tower
- $Q_{wind} = 12.043\,N/m$, which is the loads per unit length on the conductor of the maximum wind hypothesis

C.5.1 Vertical forces

The vertical forces of one conductor bundle can be calculated as stated in Equation (10.20). Two calculations will be performed as an example; firstly the vertical force in a suspension tower with the wind hypothesis and secondly for the angle tower with heavy load hypothesis:

$$F_V = m_c \cdot g \cdot n_{cond} \cdot a_{weight} + n_{ins} \cdot m_{ins} \cdot g = 6.326 \cdot 1 \cdot 690.8 + 1 \cdot 608.22 = 4978.22\,N \quad \text{(C.25)}$$

$$F_V = m_c \cdot g \cdot n_{cond} \cdot a_{weight} + n_{ins} \cdot m_{ins} \cdot g = 46.056 \cdot 1 \cdot 279.66 + 2 \cdot 608.22 = 14097.02\,N \quad \text{(C.26)}$$

Where $m_c \cdot g$ is equal to the conductor weight, which considers ice if there is.

For the other conditions, the calculation will be the same, changing the values for the weight span and the conductor loads.

C.5.2 Transversal forces

For the transversal forces, two components need to be calculated: the angle resultant and the wind effect according to Equation (10.23). In this example, only the wind hypothesis will be studied, for both suspension and tension towers.

For the suspension tower, the angle resultant will be disregarded, as no deflection angle can exist for the designs provided by the software for this kind of towers. Therefore, only the wind effect will be calculated using Equation (10.22):

$$F_{wind} = Q_{wind} \cdot a_{wind} \cdot \cos\alpha \cdot n_{cond} = 12.043 \cdot 216.0 \cdot \cos 0 \cdot 1 = 2601.3\,N \quad \text{(C.27)}$$

The total transversal load on the suspension tower is calculated with Equation (10.23):

$$F_T = F_\alpha + F_{wind} = 0 + 2601.3 = 2601.3\,N \quad \text{(C.28)}$$

For the angle tower, the angle resultant will have a value, calculated according to Equation (10.21):

$$F_\alpha = (H_{T1} + H_{T2}) \cdot \sin\alpha = (20216 + 18391) \cdot \sin\frac{3.27}{2} = 1101.54\,N \quad \text{(C.29)}$$

Since the angle tower has two neighbor spans that correspond to different blocks, the first span and the second span will have different horizontal tensions. The first span has the same horizontal tension as the suspension tower of study, whereas the second one has the value specified at Table C.3.

The wind load is then calculated:

$$F_{wind} = Q_{wind} \cdot a_{wind} \cdot \cos\alpha \cdot n_{cond} = 12.043 \cdot 216.8 \cdot \cos\frac{3.27}{2} \cdot 1 = 2609.86\,N \tag{C.30}$$

The total transversal force is:

$$F_T = F_\alpha + F_{wind} = 1101.54 + 2609.86 = 3711.4\,N \tag{C.31}$$

C.5.3 Longitudinal forces

For the longitudinal forces calculation, two conditions will be considered: Unbalance hypothesis for the suspension tower and Conductor break for the angle tower.

For the unbalanced condition with suspension towers, the corresponding percentage of horizontal load that will appear due to the unbalance is equal to a 15%. Therefore, according to Equation (10.24), the longitudinal force is calculated as:

$$F_L = \delta \cdot H \cdot n_{cond} \cdot \sin\alpha = 0.15 \cdot 42670 \cdot 1 \cdot \cos 0 = 6400.5\,N \tag{C.32}$$

For the angle tower, the conductor break hypothesis yields a horizontal force factor of 100%. The longitudinal force is calculated as:

$$F_L = \delta \cdot H \cdot n_{cond} \cdot \sin\alpha = 1 \cdot 42670 \cdot 1 \cdot \cos\frac{3.27}{2} = 42652.6\,N \tag{C.33}$$