Methodology for sizing lightning rod cables of transmission lines

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ABSTRACT
The lightning rod cables of transmission lines are elements intended to protect against lightning discharges, but what determines their sizing is the current to be drained during a fault to the earth. This article presents a methodology to establish, quickly and accurately, the gauge and exchange points of the lightning conductors of transmission lines, through the simulation of the system and analysis of the single-phase short-circuit currents using the Alternative Transients Program (ATP) as a tool.

Keywords: Short Circuit, Transmission Line, Lightning Cables, ATP.

1 INTRODUCTION

In transmission line projects, the correct sizing of the guard cables can have significant impacts on the costs of the project through the value of the cable and the adequacy of the structure in order to support the weight and traction imposed by the cable. The dimensioning using a computational tool provides speed and precision in the results, contributing to the cost reduction of the basic project project, since it is only after the definition of the cables that other steps are completed, such as, for example, the calculation of mechanical forces and electrical losses by electromagnetic induction.

The sizing is carried out through the analysis of the short circuit currents that circulate in the occurrence of a single-phase fault, many times this defect originates from the insulation failure of the insulator chain, either by breaking the dielectric or by physical damage from vandalism, then the contact of a phase with the tower occurs, This, in turn, represents an electrical point connected to the lightning rods and to the earth through grounding at the foot of the tower. In this way, part of the current propagates to the earth through the grounding in the foundation of the structure and through the guard cables.

The ONS determines that lightning rod cables must withstand, without damage, "to the circulation of current associated with the occurrence of a free single-phase short circuit in any structure of the LT-AC for a duration corresponding to the time of action of the rear protection" [1].

The damage can be caused by the heating caused by these high fault currents and the exposure time to which the cables are subjected. The current limits per time at which the cables do not suffer damage to their electrical and mechanical characteristics are found in NBR 8449 [2].

For the sizing and calculation of DC currents, NBR 8449 [2] determined a way to estimate currents, but being a method for only one cable, the methodology is currently outdated due to the short-circuit capacities determined by ONS for new projects. In the 1970s there was a study [3] that presented equations to quantify them during an eventual shortage, which at the time, for the processing capacity of computers was a good solution, but even so, it did not provide for a cable change. More recently, in 2003 [4] a methodology for simulation in EMTP/ATP was developed, where it would be possible to represent all the variables involved. A great advantage of the method is that the growing use of OPGW cables, which have, at their core, optical fibers that are currently widely disseminated for communication between substations and even rental of the communication channel to TV and Internet companies by the broadcasters, does not represent major problems for the calculation, since ATP can easily achieve it with non-massive cables.

The problem with simulation using ATPdraw's graphics, which is only an ATP graphics processor, is the time involved in modeling and executing the methodology. Thus, the present article proposes the simulation without using ATPdraw, generating the files for direct use of ATP through Excel VBA or a program developed in any other programming language.

2 METHODOLOGY FOR SIMULATION

The beginning consists of line modeling, when using ATPdraw, this occurs graphically. The line is modeled considering the equivalent of the substations, representing them as ideal sources associated with impedances, which will represent the characteristics of the machines and will be adjusted proportionally to obtain the values of single-phase short circuit between the busbars and the grounding networks according to the project.

It is important to model the span-to-go transmission line (LT), as each tower in the line is a point of interest, so the conductor cables, lightning rods and tower geometry must be introduced through the *Line Constants* (LCC) of ATPdraw. Thus, for the different spans and for the different combinations of guard cables, there will be different *LCCs.* Between a *LCC* The electrical point of the tower must be modeled, using resistors connected to the lightning rod outputs of the *LCC* and the earth through tower foot resistance.

3 SIMULATION ALGORITHM

Once the initial model of the line is ready, the simulation begins and the entire process can be summarized in an algorithm:

1. The first step is modeling, as explained earlier.
2. The characteristics of the machines are adjusted until the values of single-phase short current between busbar and earth mesh are obtained, according to the project or indication of the ONS [5] in the substations.
3. The fault is applied to the first tower on both sides of the LT and it is checked that the cables support the currents that circulate through them. This determines the cable with the highest current carrying capacity to be used.
4. The fault in the first tower is applied after the exchange of lightning cables towards another substation, in order to verify that the current returning to the substation is within the capacity of the cables of lower capacity. If supportable, *the LCC* for these cables can be moved back, decreasing the overall length of the larger capacity cable. If it doesn't, go ahead and check if it supports again. If the change in the *LCCs* went in one direction and had to change, the exchange point on the other side of the TL is analyzed and the process is repeated.
5. When obtaining the ideal point on both sides, the total impedance of the TL has changed in relation to the initial one, so steps 2, 3 and 4 are repeated until the exchange points are no longer changed and the substations have their single-phase short values according to the project.
6. Once the modeling with all the ideal characteristics is obtained, the single-phase point-to-point fault is applied to obtain the current distribution throughout the TL.

By using graphic elements, this process becomes time-consuming and repetitive, since you have to move the *LCC* to be used, remove what does not meet the specifications, change the characteristics of the machine, check if the value corresponds to the desired one, change it again and etc. in addition to exposing the simulation to human errors caused by the repetitive process. Thus, this is an excellent tool but there is a relatively high time cost.

4 METHODOLOGY FOR PROGRAMMING

When it was realized that ATPdraw is just a graphics engine of ATP, a range of possibilities arises from the understanding that only correctly constructed ASCII (.txt format) cards are needed, which any programming language is capable of accomplishing.

Analyzing the card that is sent to ATP by ATPdraw during the simulation and making use of ATP *Rule Book* [6] To understand each command, it can be seen that it can be divided into five parts, the command to be executed with the definition of the constants for the simulation, the electrical connections, the inclusions of the *LCCs*, the characterization of the optimal source, and the shutdown commands.

Once you've mastered the construction of each part, the modeling step consists of creating the *LCCs* The work is necessary for the simulation and the work then boils down to generating the text files, naming the connection points appropriately, so that when running it in ATP it is easy to find the point, the currents and determine in which direction they go and then import the values obtained from the output card and table them.

5 CASE STUDY

For the case study, a fictitious TL was used. As a hypothesis, it was used the idea that the TL under study was generated from the sectioning of an old line, where the existing lightning cables are two alumoweld 7#9.

The purpose of this study is to change as little cable as possible, since ACSR cable is considerably more expensive than alumoweld 7#9 cable, the less Dotterel is used, the lower the cost of the project.

For the cases under study, the TL data used are:

- Voltage: 440 kV
- Beam: 4 x Grosbeak ACSR per phase with 40 cm spacing between subconductors
- LT length: 84.2 km
- Length of the span at the exit of the SEs: 100 m
- Basic span: 400 m
- Tower Foot Resistance: 20 ohms
- Ground Meshes: 1 ohm
- Single-phase short-circuit capability on the bus of the SEs: 50 kA
- Fault Clearance Time: 250 ms
- Earth resistivity: 1000 ohms*meter

The data of the geometric positions of the phases in the structure are presented in Table 1.

Table 1 – Geometric arrangement of cables.

	HORIZONTAL	VTOWER	VMID
PHASE A	0,0	25,03	16,00
PHASE B	-9,0	20,23	11,20
PHASE C	9,0	20,23	11,00
GUARD A	-7,2	31,88	22,85
GUARD B	7,2	31,88	22,58

The cables to be used as lightning rods are shown in Table 2.

Table 2 – Lightning Arrester Cables and Current Capacities

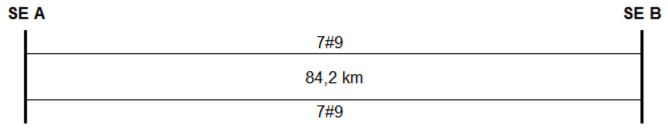
Cape	Current Capacity (kA)	DC Resistance at 20º C
CAA DOTTEREL	26,0	0,3221
ALUMMELD 7#9	7,4	2,0429

With this data, it is possible to design and verify the behavior of the TL according to the cable combination used. Thus, three cases are evaluated:

5.1 A. CASE 1

In this case, the LT will only have the alumoweld 7#9 cable, from end to end, as shown in Figure 1.

Fig 1 – Detail of the lightning rod cables in case study 1.



The TL in this case has symmetry of the left and right lightning rod cables, so the current that circulates through one of them is equal to that which circulates through the other.

There is also symmetry regarding the sides of the TL, the two SEs have the same level of short-circuit in the busbars and the TL is large enough to obtain transition points for the lightning rod cables, so what happens on one side of the TL also happens on the other. The short-circuit levels are:

- Substation bus short-circuit level (SE): 50 kA
- 1st go from the SE:
  - Short current: 49.38 kA
  - Maximum current at 7#9: 17.79 kA

At this point it is already possible to observe that, for this level of short circuit, the alumoweld 7#9 cable does not meet the currents that circulate. In the event of a shortage, it will heat up to a temperature higher than the limit stipulated by the standard.

By applying a fault to each structure, it is possible to map the fault current circulating from the phase to the structure, where it then splits between the lightning rods and what travels down the structure.

Figure 2 shows the distance in kilometers from SE A and the single-phase short-phase values for these points. In other words, as an example, in the structure located 20 km from SE A, the single-phase short-current in it is close to 20 kA. The minimum fault current was 15.68 kA, missing 42.1 km away from SE A.

The amount of current that descends through the grounding of the structures along the TL is shown in Figure 3.

Fig 2 – Single-phase short-phase level curve at each point of the TL – case 1

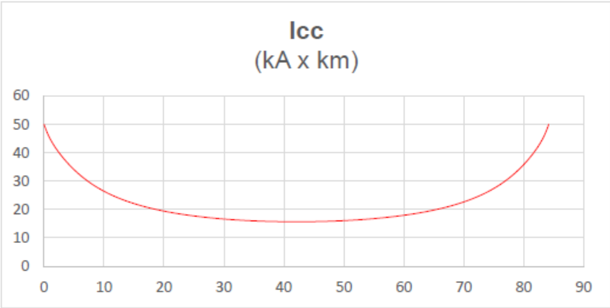
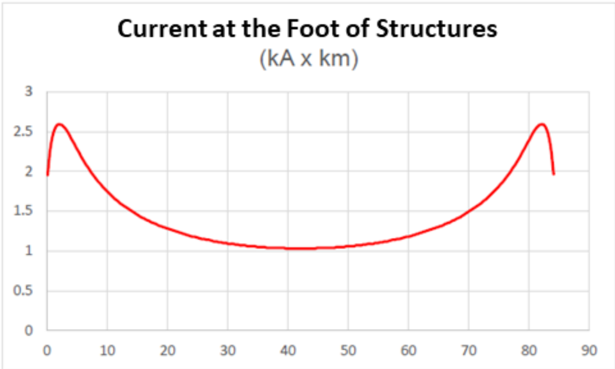


Fig 3 – Current contour line at the foot of the tower at each point of the TL – case 1



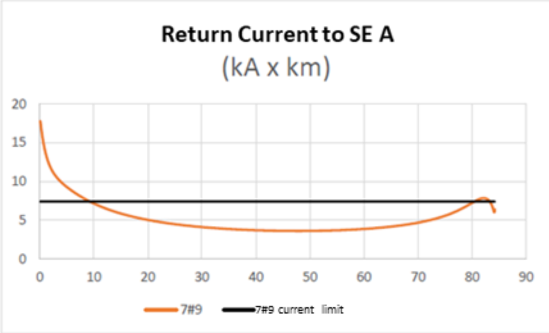
Near the subs, the current that descends through the ground is greater, but it represents a lower percentage value than in the middle of the TL. Because there is no lightning conductor transition, the curve, after the peaks of the ends, does not show jumps.

The analysis of the current in lightning rod cables, for clarity, is divided by the direction that follows it. In Figure 4, the direction adopted is that of the current to SE A.

Figure 4 shows the value of the current that, after the single-phase fault, returns to SE A. The current limit is also represented in the alumoweld cable 7#9, so that the points where the currents are higher than allowed are more clearly visible.

Thus, it can be observed that all points where the current curve in the cable is higher than the limit curve points out that the cable does not support the circulating currents. From the symmetry, it is known that the current curves for SE B have the same shape.

Fig. 4 – Current in the lightning rod – case 1.

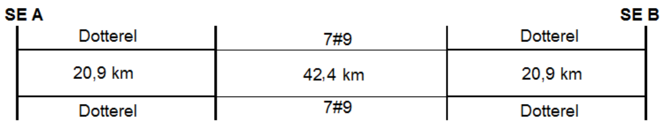


In this case, the current capacity of the adopted cables does not meet the needs of the LT. At all points where the current limit is exceeded, it indicates that there would be overheating of the cable, which could cause partial or even permanent damage to the lightning rod cables.

5.2 B. CASE 2

In this case, the LT will have Dotterel ACSR cables in the vicinity of the SEs and, when possible, transition to two 7#9 alumoweld cables, as shown in Figure 5.

Fig. 5 – Detail of the lightning rod cables in case study 2.



The TL in this case has symmetry of the left and right lightning rod cables, so the current that circulates through one of them is equal to that which circulates through the other.

There is also symmetry regarding the sides of the TL. The two SEs have the same level of short-circuiting in the busbars and the TL is large enough that it is possible to obtain transition points for the lightning rod cables, so what happens on one side of the TL also happens on the other.

- Short circuit level on the bus of the SEs: 50 kA
- 1st go from the SE:
  - Short current: 49.68 kA
  - Maximum current at Dotterel: 16.92 kA
  - Current going down the tower: 1.7kA

At this point it is already possible to observe that, for this level of short circuit, the Dotterel ACSR cable meets the currents that circulate. In the event of a shortage, it will not heat up to a temperature higher than the limit stipulated by the standard.

It is also noteworthy that 68.12 % of the fault current at this point returns to SE A, 3.42 % descends to earth through the structure and the rest goes to SE B.

- Transition Point
    - Transition 2 x Dotterel – 2 x 7#9:

      Short Current: 22.14 kA

      Maximum current at 7#9: 7.35 kA

      Current going down the tower: 0.81 kA

The short is given in the structure following the one that makes the transition and the return is observed through the cables of lower capacity. Thus, it can be seen from the values that the transition takes place in a suitable place, where there is no slack for the cable transition to approach the SE A.

By applying a fault to each structure, it is possible to map the fault current circulating from the phase to the structure, where it then splits between the lightning rods and what travels down the structure.

Figure 6 shows the distance in kilometers from SE A and the single-phase short-phase values for these points. In other words, as an example, in the structure located 20 km from SE A, the single-phase short-current in it will be greater than 20 kA. Even with the change of cables the curve remains smooth, this demonstrates that the impedance of the LT is seen as a whole for the fault and the curve adjusts for the total impedance of the LT. The minimum fault current was 17.5 kA, missing 42.1 km away from the SE.

Fig. 6 – Single-phase short-phase contour line at each point of the TL – case 2

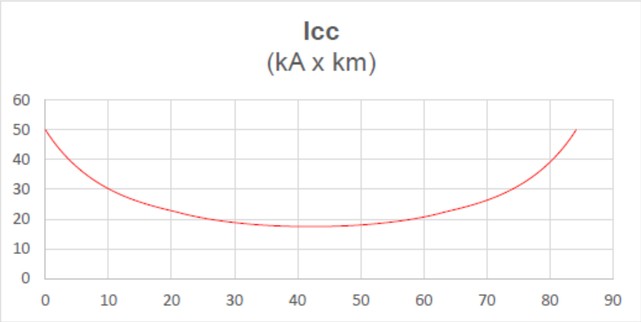
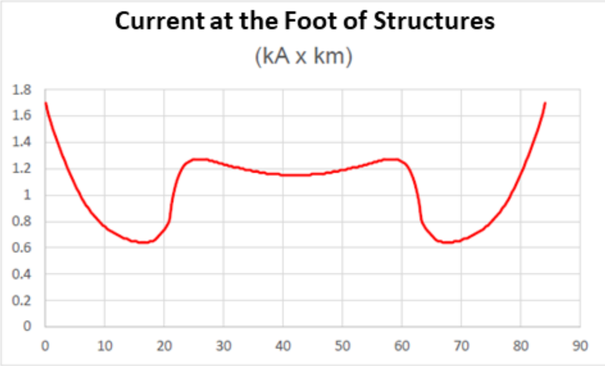


Figure 7 shows the amount of current that descends through the grounding of the structures along the TL. Near the subs, the current that descends through the ground is greater, but it represents a lower percentage value than in the middle of the TL.

Figure 7 – Current contour line at the foot of the tower at each point of the TL – case 2



The behavior of the curve shows that, unlike the single-phase short-phase level curve at each point of the TL, the current that descends to the grounding of the structures is punctually sensitive to the change in the impedance of the lightning rods. In the middle of the line, in the section where lightning rod cables have a higher impedance, the tower tends to absorb a higher current, due to the greater equivalent resistance seen from that point.

Just like in case 1, the current is higher at the ends due to the high level of shorting. Comparing percentages it can be seen that at the end 1.7 kA of 49.68 kA is absorbed, which represents about 3.42 % and at 40 km from SE A it drops 1.15 kA of 17.58 kA, about 6.57 %.

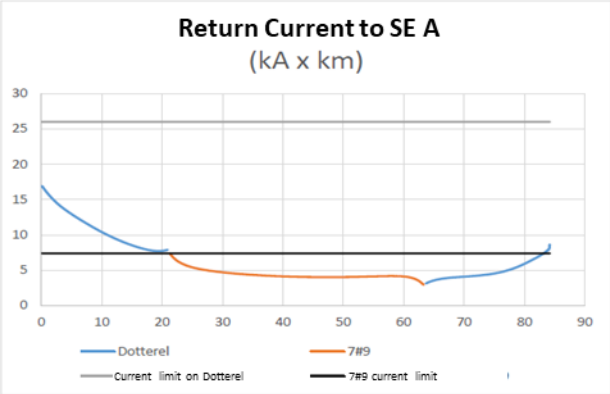
The analysis of the current in the cables, for the sake of clarity, is divided by the direction that follows it. In Figure 10, the direction adopted is that of the current for SE A. Due to the symmetry between the radii on the left and right side of the line, the representation of the two sides is equal, eliminating the need for a graph for each side.

Figure 8 shows the value of the current that, after the single-phase fault, returns to SE A. The current limit is also represented in the 7#9 alumoweld cable and in the Dotterel ACSR, so that the points where the currents are higher than allowed are more clearly visible.

It can also be observed that the Dotterel CAA has a large clearance at the exit of SE A and is well away from its limit.

The section where the alumoweld 7#9 cable is used starts where there is no gap, the cable is very close to its limit. Due to symmetry, the current curves for the B substation have the same shape.

Figure 8 – Current returning to SE A in lightning rods – case 2.



In this case, the current capacity of the adopted cables meets the needs of LT. There are no points where there would be harmful heating of the cables. The Dotterel ACSR cable is used in four sections of 20.9 km, thus totaling 83.6 km.

5.3 C. CASE 3

In this case, LT will have Dotterel ACSR cables in the vicinity of the SEs and, when possible, will transition one of the cables to alumoweld 7#9. When it is possible again, the second Dotterel ACSR will be replaced by another alumoweld 7#9. The same process was performed for the other side of the TL, as shown in Figure 9.

Fig. 9 – Detail of the lightning rod cables in case study 3.

SE A — SE B

Dotterel	Dotterel	7#9	Dotterel	Dotterel
2.1 km	13.6 km	52.8 km	13.6 km	2.1 km
Dotterel	7#9	7#9	7#9	Dotterel

The TL in this case does not have complete symmetry of the left and right lightning rod cables, so the current that circulates through one of them is not the same as that which circulates through the other. There is symmetry regarding the sides of the TL, the two SEs have the same level of short-circuiting in the busbars and the TL is large enough that it is possible to obtain transition points for the lightning rod cables, so what happens on one side of the TL also happens on the other

- Short circuit level on the bus of the SEs: 50 kA
- 1st go from the SE:
  - Short current: 49.67 kA
  - Maximum current at Dotterel: 17.04 kA
  - Current going down the tower: 1.71 kA

At this point it is possible to observe that, for this level of short circuit, the Dotterel ACSR cable meets the currents that circulate. In the event of a shortage, it will not heat up to a temperature higher than the limit stipulated by the standard.

It is also noteworthy that 68.61 % of the fault current at this point returns to SE A, 3.44 % descends to earth through the structure and the remainder goes to SE B.

- Transition Point
  - Transition 2 x Dotterel – Dotterel + 7#9:

    Short Current: 42.42 kA

    Maximum current at 7#9:7.24 kA

    Maximum current at Dotterel:23.41 kA

    Current going down the tower: 1.51 kA

The short is given in the structure following the one that makes the transition and the return is verified by the cables of lower capacity. Thus, it can be seen from the values that the transition takes place in a suitable place, where there is no slack for the cable transition to approach the SE A.

- Dotterel Transition + 7#9 - 2 x 7#9:

  Short Current: 42.42 kA

  Maximum current at 7#9:7.24 kA

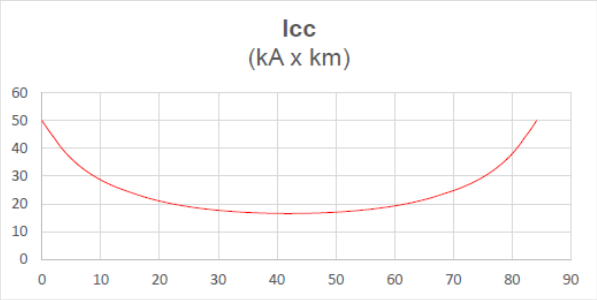
  Current going down the tower: 1.51 kA

Due to the symmetry of the line, the transitions of 2 x 7#9 – Dotterel + 7#9 and Dotterel + 7#9 – 2 x Dotterel have the same values as those shown above. In all transitions, the cables involved work close to their limits, which means greater financial and technical efficiency.

By applying a fault to each structure, it is possible to map the fault current circulating from the phase to the structure, where it then splits between the lightning rods and what travels down the structure.

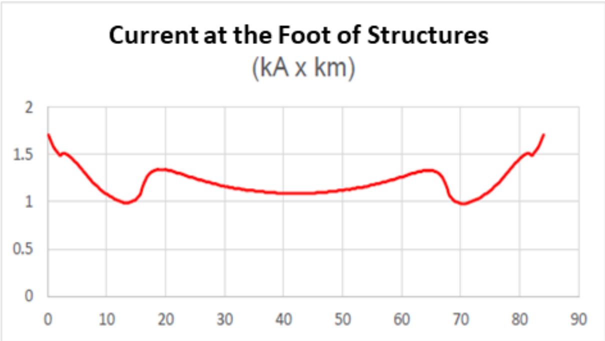
Figure 10 shows the curve of the single-phase short value at each point of the TL. Similarly to case 2, the fault curve by distance from SE A does not suffer from peaks or jumps caused by stretches with different impedances. The minimum fault current was 16.56 kA, missing 42.1 km away from SE A.

Fig. 10 – Single-phase short-phase level curve at each point of the TL – case 3.



In Figure 11, the tower, whenever the total impedance of the cables increases, starts to absorb a higher percentage current in relation to the total single-phase fault current. In this case, the current absorbed by the structure is not much less than 1 kA, which represents a small relief for the cables.

Figure 11 – Current contour line at the foot of the tower at each point of the TL – case 3.

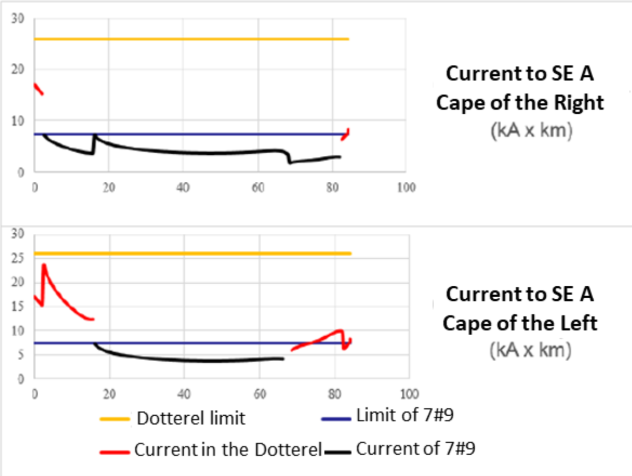


The analysis of the current in the lightning rod cables, for greater clarity, is shown in two graphs that together represent what happens in the two cables, so that the behavior of the right and left cables is clearly visible.

Figure 12 shows two groups of curves, the one above refers to the cables that are to the right of the structure while, and the ones below are the cables to the left. It is interesting to analyze the behavior of the curves simultaneously and observe the impact that one side has on the other.

At the outlet of the SE A, there are two Dotterel ACSR lightning rod cables and the curves of the two are the same, when the transition to alumoweld 7#9 is made to the right of the structure, the left side has a peak in its short-circuit level, approaching its maximum capacity.

Fig. 12 – Current returning to SE A in the lightning rods – case 3.



At the point of the second transition there is the discontinuity on the left side, the peak at this point occurs on the right side and takes the two 7#9 cables to their full use, and from there the curves remain the same until the next transition. From the symmetry, it is known that the current curves for SE B have the same shape.

In this case, the current capacity of the adopted cables meets the needs of the LT in a well-optimized way. There are no points where there would be harmful heating of the cables. Two Dotterel ACSR cables are used in two 2.1 km sections and one in two 13.6 km sections, totaling 31.4 km.

6 CONCLUSION

A methodology for the sizing of transmission line lightning conductors was presented, consisting of, through modeling and simulation, evaluating the short currents according to the Brazilian standard (NBR) 8449, seeking the transition point of the lightning rods to ensure that there are no overheating points and to achieve substantial savings in cables.

The design of lightning rod cables using ATP offered a good alternative to the calculation methods. It presented a certain time between modeling the system, simulating and tabulating the currents that circulate during a fault, however the reliability attributed to the method is very high due to the considerations of the most diverse variables.

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