COMSOL modeling of the lightning-generated electric field distribution in a chain of insulators of a 115 kV power transmission line.

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Abstract. The transmission lines installed in our city, to the outskirts of it and in the rest of the national territory produce a level of emissions of electric field, these levels vary depending on the physical disposition of the drivers, the distance between spans, the voltage level of the line, among others. These values must respect the exposure limits for individuals, as stipulated in Article 14 of RETIE. In this work will be developed a study of distribution of the electric field along a chain of insulators standard of tempered glass of a transmission line of 115 kV with the aid of the software COMSOL Multiphysics, to the impact of an atmospheric discharge on the storage cable with the help of ATPDraw software, taking into account variations in the value of the earthing resistance of the structure. With the electric field distribution values obtained by means of simulations carried out in the COMSOL Multiphysics software, comparisons are made of the magnitude of the obtained field, taking as a reference the stable state of the system without condition of pollutants. Initially a simulation of a transmission line of 115 kV is performed in the ATPDraw software, analyzing the lightning impulse generated on the guard cable, at different values of grounding resistance, to determine the waveform and reached value of overvoltage in the insulator chain. Then the overvoltage signal obtained with the help of ATPDraw software is recreated in the COMSOL Multiphysics software, to be able to visualize the distribution and behavior of the electric field along the chain, taking into account the different factors involved in the process, pollutants such as salinity, themes such as travelling waves etc. and thus determine possible line isolation failures by comparing the values achieved by simulating in COMSOL Multiphysics with respect to the CFO of the insulator chain.

1. Introduction
Colombia has a high density of lightning to ground because it is located in the Intertropical Confluence Zone, so it has one of the largest lightning activities on the planet. Therefore, it is essential for the design and commissioning of a power transmission line, to consider the electrical and constructive characteristics of the line and the location where it is installed. These parameters are necessary to comply
with the number of outputs required by the network operator or failing that, which is established in resolution CREG 025 of 1995, which establishes that for voltage levels equal to or greater than 220 kV, they are 3 outputs per 100 km of line per year. For this reason, by means of an isolation coordination, it must be demonstrated that the number of outputs calculated is below the established value.

For a network of 115 kV (study voltage level) there is no regulation around the requirement of a certain number of outputs of the lines by lightning, however, the resistivity of the soil of the installation of the line and the grounding resistance must be considered. For example, in the department of Meta between the municipalities of Villavicencio and Guamal, the company Electrificadora del Meta S.A. E.S.P (EMSA) for the transmission line between the Ocoa and Guamal substations proposed a maximum value of 10 outputs per 100 km of line per year, since they take into account the high resistivities of the installation grounds of the line, because the greater the grounding resistance, exist a high probability that flash over will occur and therefore greater is the number of outputs that can occur [1]. One of the anomalies within an electrical power system are the overvoltages due to lightning that cause a greater electrical stress in the transmission systems, causing the electrical damages due to the natural phenomenon, since the transmission lines cover a very large area within the land where they are installed, given that their sections cover long distances and cross lands exposed to different types of climates.

Therefore, the present paper models with the help of Comsol and ATP software the electric field distribution in a chain of insulators of a 115 kV transmission line with contamination, to visualize the electric field values that occur when the network is in normal operation and when lightning strikes the structure.

2. Methods

2.1. ATPDraw modeling of a transmission line in the event of an atmospheric discharge.

For the present study, the results of the fast front overvoltages in a typical 115 kV line are presented, in order to obtain the most representative overvoltage values in the event of an atmospheric discharge in the area. Therefore, the above is considered from the NTC 4552-1 standard, taking into account the conditions under which the line operates. In addition, the IEC 60815-2 standard is taken into account in order to consider the parameters of the area in which the transmission line is operating. The peak lightning current magnitude is 43 kA and its representative current shape is the standard atmospheric impulse (10 / 350 µs). This allows to obtain the waveform of the overvoltage originated at the point of impact of the transmission tower.

It is essential for any type of simulation to select the appropriate models for the lightning surge analysis scenario. For the modeling of each of the elements of the system, the standard IEC 60071-4 [2], [3], Standard NTC 4552-1 [4] and [5] have been taken into account.

In the particular case of Colombia, the measurement data correspond to studies carried out with different measurement methods. The lightning current amplitude was estimated by means of vertical electric field measurements carried out in 1995 by means of a parallel plate antenna, previously calibrated in the laboratory using a high resolution digital oscilloscope and associated measuring equipment. These data were compared with those recorded by the TSS-420 storm sensor in operation at the National University facilities in Bogota. The impact distance was calculated using information provided by the Colombian lightning location network RECMA.

Figure 1 shows the comparative probability results between the values given by CIGRE in 1979 for records taken in non-tropical latitudes and those estimated in four tropical countries: Brazil (Cachimbo station, State of Minas Gerais, 1996), Rhodesia (Anderson, et. al., 1954), Malaysia (Lee, et. al., 1979) and Colombia (Torres, et. al., 1995). This graph shows the higher probability of negative lightning return current magnitude in tropical zones (Brazil, Malaysia, Colombia and Rhodesia), with respect to non-tropical zones (CIGRE) [4].
Figure 1. Cumulative probability curve for negative return current [4].

The surge impedance of the towers of a transmission line varies along the tower and is affected by the wave propagation time, so it depends on the details of the structure [6]. Therefore, the tower can be represented as a single-phase transmission line with an impulse impedance and a wave propagation speed equal to that of light [6].

For power systems, the model of atmospheric impulses must take into account that the reflections of the traveling wave due to the impact of lightning must not return to the analysis node in order to avoid adding to the wave that arrives at that point. This is achieved by modeling a line of infinite length, i.e., a line impedance that avoids reflections of the traveling wave on the transmission line [7].

To determine the length of the chain or isolation distance, the IEC 60815-2 and IEC 60071-2 standards must be considered. Therefore, the zone in which the transmission line is located must be determined in order to obtain the RUSCD, which according to IEC 60815-2 is defined as the normal unified specific leakage distance for each level of contamination. Figure 2 shows the RUSCD or USCD value depending on the level of contamination present in the study area.

For standardization purposes, five classes of contamination characterizing the site are defined in IEC 60815-2 [8], from very light contamination, to very heavy contamination as:

a. Very light
b. Light
c. Medium
d. Heavy
e. Very heavy
Figure 2. RUSCD as a function of the severity of the contamination class in the area [8]

The procedure for determining the isolation distance is based on equation (1).

\[ USCD_C = RUSCD \times K_a \times K_{ad} \]  

(1)

Where:
- \( USCD_C \) = Corrected unified specific leakage distance.
- \( RUSCD \) = Nominal unified specific creepage distance
- \( K_a \) = Altitude correction factor
- \( K_{ad} \) = Correction factor according to insulator diameter

2.2. Transmission line modeling.

For the modeling of phase conductors against atmospheric impulses for transmission lines, the Bergeron model of the LINE CONSTANTS subroutine of the ATP was considered, taking into account that it is a model of conductors with constant distributed parameters, which is based on wave propagation in a defined section. The frequency used for the model is 100 kHz [7]. In order to know the simulated overvoltage values at any point of the transmission line, the input values are defined for the ATP (Alternative Transient Program) software - Version 6.0.

The electrical parameters of the system under study are
- Rated voltage: 115 kV
- Maximum service voltage Um: 123 kV
- Typical line span: 300 m

The parameters of the phase and guard conductors are presented in Tables 1 and 2.

Table 1. Phase conductor parameters \(^a\).

| Parameter                          | Value                  |
|------------------------------------|------------------------|
| Conductor HAWK ACSR 477 kcmil     |                        |
| (typical conductor for this voltage level) |                        |
| Aluminum wire diameter             | 3.439 mm               |
| Galvanized steel wire diameter     | 2.674 mm               |
| Conductor outside diameter         | 21.79 mm               |
| Steel section                      | 39.31 mm\(^2\)         |
| Aluminum Section                   | 241.5 mm\(^2\)         |
| Total Section                      | 281 mm\(^2\)           |
| DC resistance of the conductor at 25 °C | 0.1198 Ohm/km         |
| AC conductor resistance at 75 °C   | 0.1432 Ohm/km          |

\(^a\) Values taken from the manufacturer's catalog CENTELSA.
Tabla 2. Guard conductor parameters \(^a\).*

| Conductor       | OPGW                  |
|-----------------|-----------------------|
| Type            | ACS (Aluminium Clad Steel) |
| Caliber         | 24SM-14.4 mm          |
| Outside diameter| 14.4 mm               |
| DC resistance   | 0.427 Ohm/km          |

**OPTICAL UNIT**

| Number of Fibers | 24 |
|------------------|----|
| Outer Diameter Fiber Container Tube | 3.2 mm |
| DC resistance    | 3.76 Ohm/km |

\(^a\) Datasheet cable OPGW 24 SM-14.4 mm

The layout of the phase conductors and guard wires in the structure for a 115 kV network is shown in Figure 3, which corresponds to a double-circuit structure in vertical configuration.

2.3. Lightning impulse source.

For the model of the atmospheric discharge that will impact the transmission tower under study, the ATP Heidler type source is used, with a peak current of 43 kA, a wave rise time of 10 µs and a decay time of 350 µs. The selected amplitude value was extracted from the NTC 4552-1 standard (Protection against atmospheric electric discharges (Lightning) Part 1: General principles - Table A.1) Medians of the peak value of the lightning return current in different areas of the planet [4].

2.4. Chain of insulators.

For the modeling of the insulator strings, voltage controlled switches were used, as proposed in [7], taking into account that the Critical Flash Overvoltage (CFO) for each of the insulator strings corresponds as shown in equation (2). Figure 4 shows the element used SwitchVC - Switch Voltage Control of ATPDraw.

![Figure 3. Arrangement and distances of phase and guard wire conductors in vertical configuration for typical 115 kV structures.](image)
\[ CFO = \left( 400 + \frac{710}{t^{0.75}} \right) \times W \ [kV] \]  

(2)

Where:

\( t \): 6 \( \mu \)s flashover time.

\( W \): Length of insulator chain.

For this article a study area is established, corresponding to the city of Bogotá located in the department of Cundinamarca, in such a way that taking a Very Heavy contamination level, the number of isolators (NA) is calculated, giving the results shown in Table 3.

| Case study | Altitude above sea level [m.a.s.l.] | Contamination level | NA (calculated) | NA (standardized) |
|------------|-------------------------------------|---------------------|----------------|------------------|
| Bogotá D.C | 2600                                | Very Heavy          | 16.4           | 17               |

Once the total length of the insulator chain has been calculated, the CFO (Critical flash Overvoltage) is calculated for each case of study according to equation (2). Thus, this value for the network in the city of Bogotá is 1452 kV.

2.5. Transmission tower structures.

This model takes into account what Sargent and Darveniza proposed for this type of structures, which corresponds to a conical model providing a constant impedance for the transmission tower [9].

- Conical Model

\[ Z_t = 60 \ln \left( \frac{\sqrt{2} \sqrt{r^2 + h^2}}{r} \right) \]  

(3)

Where:

\( Z_t \): Surge impedance of the structure.

\( h \): Tower height (m).

\( r \): Tower base radius (m).

\( c \): Speed of light \((3 \times 10^8 \text{ m/s})\).

The structure data are shown in Figure 3 to obtain the surge impedance values of the structure for each modeled part. Considering the above, a distributed parameter model of a Clarke-type single-phase line was implemented to represent the transmission structures, considering a typical grounding resistance value for 115 kV structures of 20 \( \Omega \). For the modeling of each of the associated structures, a LINEZ characteristic impedance segment used by the ATP software was considered.

3. Data export from ATP to Comsol software.

Figure 4 shows a section of the modeled system and the site of the impact of the atmospheric electric discharge and where the electric overvoltage presented in the chain of insulators of the transmission line is evaluated. Figure 5 presents the result of the overvoltage obtained with the help of the ATP software, considering a grounding resistance of 20 \( \Omega \). This signal obtained and shown in Figure 5 is exported to the Comsol software to visualize the electric field distribution along the insulator chain.
Figure 4. Measurement terminal, overvoltage signal tower adjacent to the impacted tower.

Figure 5. Overvoltage due to atmospheric discharge with 20 $\Omega$ grounding resistance.

4. Results Potential and electric field distribution along the insulator chain of the 115 kV line subjected to atmospheric discharge and contamination.

Figure 6 shows the case study where an atmospheric discharge impacts the transmission tower and the overvoltage induced in the terminal corresponding to the grounded part of the transmission tower is obtained and imported into the Comsol software. In this way, the resulting electric field is visualized in
that area at the time of the highest overvoltage present and to determine if there is a break in the dielectric rigidity of the air.

This overvoltage presents a peak value of 435 kV in the fitting that allows fixing the insulator chain in the crossarm, which allows defining the distribution of the potential along the chain. As we know, this overvoltage does not interfere in the normal operation of the system, since it is within the range of support of the insulator chain, better known as the CFO. However, we seek to study and analyze the distribution of the potential and electric field in this small instant of time where this overvoltage is generated.

![Image](image_url)

**Figure 6.** Potential distribution in a chain of insulators in the event of an atmospheric discharge on a crossarm or structure.

The potential distribution is studied with the first peak of the imported ATP wave, corresponding to a time $t = 1.36 \mu s$ as the most critical case. Figure 7 shows the behavior of the electric potential along the insulator chain.

Figure 7 shows a peak value of 435 kV up to an arc length of 354 mm where the length of the fitting plus the skull attached to it is positioned. Subsequently, the potential of the other insulator units can be detailed from top to bottom according to figure 6 when it behaves as a constant, it represents the section comprised by the junction of the bolt of the first insulator and the skull of the second insulator. Finally, the interaction of the cement and the glass in each insulating unit is observed, causing small protuberances to appear on the curve, thus showing how the potential tends to decrease at that instant of time.
The results obtained show that the concentration of pollution in the surface layer of the insulator string does not impact the results of the electric potential along the string, i.e. there is no variation in the increase of the potential even when it is affected by an atmospheric discharge.

The distribution of the electric field in the center of the chain of insulators operating normally and without contamination is shown in Figure 8, which highlights a higher level of electric field magnitude in the energized part (115 kV line), and as the insulation level is increased approaching the equipotential connection of the tower, the level of the field magnitude decreases reaching a value of 0 kV/cm. It can be observed that the distribution of the electric field magnitude in the first 3 insulators is reduced from
8.2 kV/cm to 3 kV/cm (electric field in the third insulator), approximately, as shown in Figure 8. This means a decrease of 63%, so that for the subsequent 7 insulators of the chain the rate of change is lower, proving the non-linear behavior of the electric field magnitude in the chain.

The distribution of the electric field along the chain considering the contamination and the incidence of an atmospheric discharge is shown in Figure 9. An increase in the electric field associated with the first peak is influenced by the contamination in the area where the transmission line operates, which has an electric field value of 72 kV/cm in the second peak, an increase of about 1.4 times the value of the electric field if the contamination had not been taken into account.

![Electric field distribution along the chain of insulators with contamination in the presence of an atmospheric discharge in a crosshead or structure by means of a line graph.](image)

Figure 9. Electric field distribution along the chain of insulators with contamination in the presence of an atmospheric discharge in a crosshead or structure by means of a line graph.

Likewise, the first peak, as indicated in the previous case, presents a value of 18.8 kV/cm between the cement that joins the skull and the glass, followed by the second peak, which increases from 51 kV/cm in the case where contamination is not taken into account to 72 kV/cm taking into account contamination. It can be observed in the study that in the case where no contamination is taken into account, the electric field in the last insulating unit is 3 kV/cm at an arc length of approximately 1595 mm, in contrast to the electric field value in the same insulating unit of 3.2 kV/cm according to Figure 9, but at an arc length of approximately 1625 mm, which evidently shows the indicated increase.

5. Conclusions.

The insulators when subjected to contamination conditions in the environment generate accumulation on its surface, which the behavior of the electric potential distribution is not subject to any variation, on the other hand, it generates interaction of the electric field with the accumulation of salinity on the surface, consequently leading to the increase of the same similar to what was found by [10], which can generate with certain particular conditions of the environment (such as those specified in this document), the generation of partial discharges on the surface of the insulator known as Flashover.

Regarding the analysis of the electric field implemented to the three-dimensional model, performed by the COMSOL Multiphysics software through the FEM, when designing a detailed geometry and being a robust analysis system, this requires computer equipment with high levels of data processing, since without this the model would take too much time in the process to obtain results or the possible non-
convergence of the model. Therefore, it is advisable to design processes in which the analysis is performed on simplified geometries or the development of dimensional models.

Is evident that when an atmospheric discharge occurs in the transmission line, the network is not always out of service, because the level of support to electrical stresses in the chain of insulators allows the system to withstand these eventualities since an adequate coordination of insulation for the line has been previously carried out.

In the evaluation of the dielectric stress of the air on one side of the insulator chain, it is observed that it does not exceed the value of the dielectric strength of the same in its total length, it is possible to think that in the first three insulators (from top to bottom) air rupture occurs, which would lead to a possible failure in the insulator chain. Therefore, thanks to the total length of the chain, the other insulators do not allow the arc to be generated between the phase-ground terminals.

The results obtained from the electric field under contamination conditions and when subjected to an atmospheric discharge, it was evidenced that the field value rises considerably on the surface of the insulator due to the conductivity of the contamination in the area, this contaminant layer damages the whole insulator. It was observed that the values of the electric field increase as it approaches the energized terminal, so that a bad maintenance to the line could cause along the chain of insulators an electrical disruption in the air and consequently an inverse flame.

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