International Conference on Lightning Protection
33rd International Conference on Lightning Protection
25 - 30 September 2016
Estoril, Portugal

Lightning Shielding Analysis of EHV and UHV Transmission Lines : On the Effect of Terrain Topography

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***Abstract*— In this paper, the Self-Consisting Leader Inception and Propagation Model –SLIM- is used to analyze the shielding performance of transmission lines, with special attention on the terrain topography effect. Transverse and Longitudinal terrain profiles are considered. It is found that a transmission line can be more vulnerable to be struck by lightning on any terrain that leads to increase the height of the conductors. In addition, the striking distance to the phase conductors strongly depends on the landform and the tower geometry, which suggests changes in the current lightning protection standards.**

Keywords- Lightning protection; shielding failure; UHV power transmission lines

I. INTRODUCTION

Because of the increasing demand of electric power, extra and ultra high voltage transmission lines are needed to transport large amounts of energy from remote generation centers until load centers in an efficient way. These transmission lines include AC, DC and hybrid transmission lines with complex geometry, reaching voltage levels up to 1.2 MV and height up to 140 m. Their lightning protection is essential, however, failure rates higher than the estimated by the Electrogeometric Method (EGM) have been reported [1].

Some factors that could affect the shielding performance of these transmission lines are the phase potential, the towers geometry and the terrain topography. This latter strongly appears to influence on the shielding of transmission lines. Thus, several studies report lightning accidents on transmission lines mainly in hilly and mountainous terrains. For instance, 73% of lightning trip outs in 500 kV transmission lines took place in mountainous terrain according to a statistic report of southern China [2]. In addition, 56% of lightning accidents in EHV transmission lines took place in mountainous areas, 26% in hills and 18% in flat areas, according to a seven years observation study in southeast China [3].

The EGM is currently used to analyze and design the lightning protection of transmission lines, taking into account the lightning exposure areas of the shield wires, phase conductors and ground [4]. Effective conductor and ground wires heights depending on the terrain topography are considered by Whitehead and coauthors in the EGM [5]. Thus, three types or terrain are taken into account: flat, hilly and mountainous. However, the EGM assumes that the striking distance to the conductors and to the shield wires do not change with the terrain topography, but it depends only on the prospective return stroke current and constants uninfluenced by the landform. Since the EGM has been calibrated with existing transmission lines of less voltage level and size, its validity on EHV and UHV transmission lines is in doubt. This has led to the development of lightning leaders models, based on the physics of the discharges. These models have been used for studying shielding performance of transmission lines [6-11], considering factors such as the voltage level, the bundle conductors configuration, the upward leaders competition, the space charge, the topography and others.

The self-Consisting Leader Inception and Propagation Model –SLIM– is a computational model based on the physics of the discharges, but unlike other models, it self-consistently computes most of the variables involved such as the upward leader current, the channel radius, the propagation velocity and potential gradient [12]. Until now, this has been used to study the lightning performance of complex grounded structures, getting results close to real observations [13]. Furthermore, preliminary studies of transmission lines have been carried out using SLIM [11][14], considering straight downward leaders with trajectories arbitrarily predefined (vertical and inclined). In other words, it has been considered a downward leader channel uninfluenced by the electric field distortion produced by grounded objects. However, field observations have shown that, before the final jump, the downward leaders get close to the phase conductors in a horizontal way [1]. In this study, it is considered a more consistent approach to represent the downward leader propagation [6]. Transverse and longitudinal terrain profiles are studied, regarding the overhead lines sag and the electric field distortion produced by the upward leaders started from the shield wires.

II. THE SELF CONSISTENT LEADER INCEPTION AND PROPAGATION MODEL –SLIM-

This model evaluates every stage involved in the upward leader formation, due to an approaching downward leader and the thundercloud electric field. This includes the first streamer inception, the unstable and stable leader inception, and the final jump. The simulation begins estimating the height of the downward leader tip at which a first streamer is initiated. Then, the inception of secondary streamers is evaluated as the downward leader continues descending until the corresponding corona charge is equal to or larger than a threshold charge (used as either 0.2 or 1 μC). This process is known as unstable leader inception.

The propagation of the upward leader is evaluated considering the thermo-hydrodynamical model of Gallimberti [15]. In this way, the potential gradient, the channel radius, the leader current and the propagation velocity are self-consistently computed. An unstable leader can continue propagating or not. In the latter case, the inception of new streamers is evaluated as before. In the former case, that is when the stable leader inception has taken place, the propagation of the upward and downward leader continues until the final jump occurs. This is evaluated as the moment when the streamer corona front reaches the downward leader tip. A complete model description can be found in [12], [16] and [17].

The downward leader is modeled as a nonuniform line charge distribution as proposed by Cooray et al. [18]. Unlike previous studies with SLIM, in this study it is considered a downward leader trajectory determined by the potential gradient in front of the negative streamer corona zone. This allows to take into account the electric field distortion produced by grounded structures or energized transmission lines. It is also considered that the downward leader advances with straight steps equal to the negative streamer corona length *Rsc*, estimated as the distance from the downward leader tip until the place where the electric field is equal to 300 KV/m. The equipotential surface passing through that point is found to evaluate the corresponding electric field, as shown in Fig. 1. Finally, the point of maximum electric field determines the direction of the next step of the downward leader. It is important to point out that the results presented in this paper are obtained by considering the effect of all the shielding and phase conductors on the calculation of the electrostatic conditions influencing the attachment process to the transmission line.

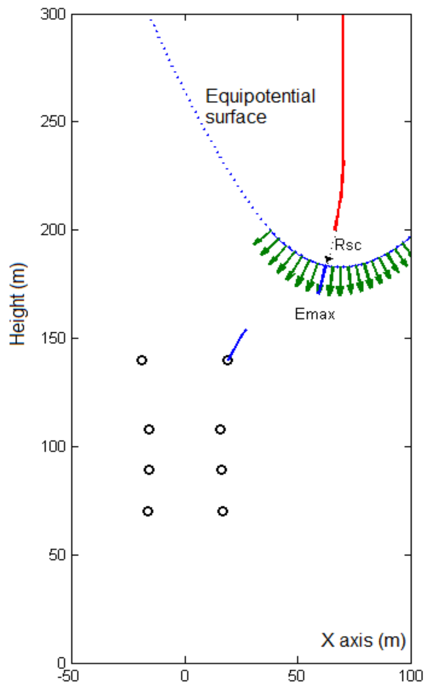

Figure 1. Cross section view of a simulated downward leader approaching a double circuit transmission line

The lightning shielding analysis of transmission lines is carried out by estimating the exposure areas for the shield wires and the phase conductors as follows.

For each conductor, a downward leader descending for multiple lateral distances is simulated. For each trajectory, the inception and propagation of an upward leader from the shield wire is evaluated as shown in Fig. 2. If a downward leader reaches the height of the shield wire without satisfying the final jump condition, it continues evaluating the inception of upward leaders from the phase conductors. In this case, the upward leader emerged from the shield wire stops propagating but keeps affecting the electric field around.

The distance between a conductor and the downward leader tip at the moment of the final jump is here referred to as the striking distance, the same geometric parameter used by the EGM for shielding analysis. After simulating a descending leader for different lateral distances, it is possible to define an exposure zone for every conductor. Notice that some downward leaders descending far away from the transmission line, do not connect with the shield wire but with some phase conductor or ground.

To estimate the shielding failure distribution among the phase conductors and shield wires, two geometrical parameters are used: the shielding success half width SSHW and the shielding failure half width SFHW. These parameters correspond to the lateral distances through which the downward leader connects to the shield wire or to the phase conductors respectively, as shown in Fig. 2. To search these parameters the bisection method is used evaluating the distance until a downward leader satisfies the final jump criterion with an upward leader initiated from a given conductor.

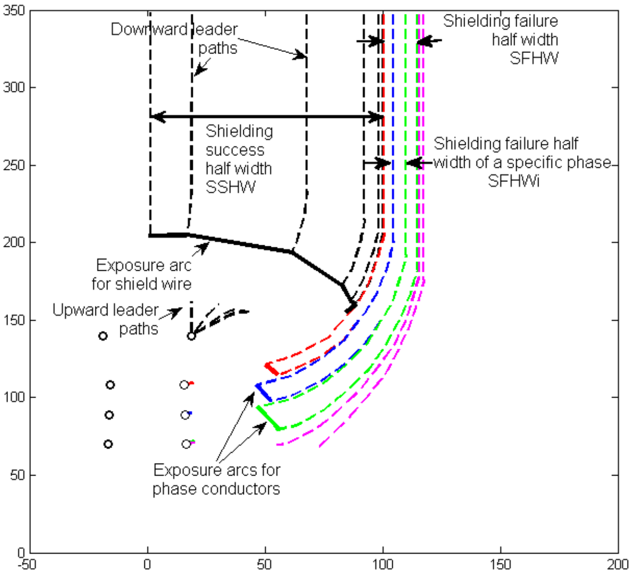

Figure 2. Shielding performance analysis of transmission lines using SLIM. The downward leader paths were calculated to obtain both, the Shielding Success half Width –SSHW–, and the Shielding Failure half Width –SFHW–. Notice that the two right-most leader paths should connect to the earth surface, being out of both the SSHW and the SFHW [19].

III. THE EFFECT OF THE TERRAIN TOPOGRAPHY

The terrain topography may strongly influence the shielding of transmission lines, since it modifies the electric field around the overhead lines. On the other hand, depending on the landform, the conductors height changes, which is a critical factor on the shielding performance.

The landscape can change in endless and complex forms. For an easier analysis of its influence on shielding of transmission lines, typical transverse and longitudinal terrain profiles are considered.

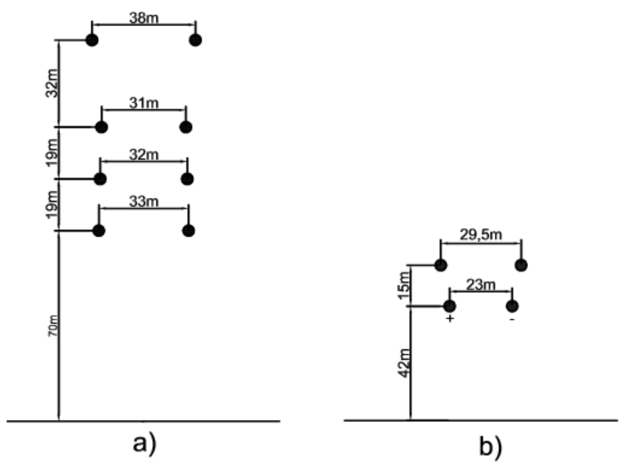

Figure 3. Studied transmission lines a) Japanese UHVAC transmission line b) UHVDC transmission line

A. *Transverse Profiles*

These terrain profiles varies transversally to the transmission lines. Four types of transverse profiles are studied: flat, mountain slope, mountain top and valley, as shown in Fig. 4. The analysis is carried out for a Japanese UHVAC transmission line [1]. Its dimensions can be seen in Fig. 3a. A prospective return stroke peak current of 14.7 kA is considered, which corresponds to the 50% probability lightning peak current in the cumulative frequency distribution reported in [20]. Previous studies have shown that the overall lightning shielding performance of this transmission line do not change significantly under variations in voltage magnitude or phase angle [19]. Thus, in this study an instantaneous voltage value at a phase angle of 90° is arbitrarily considered for each phase conductor, with a line voltage of 500 kV.

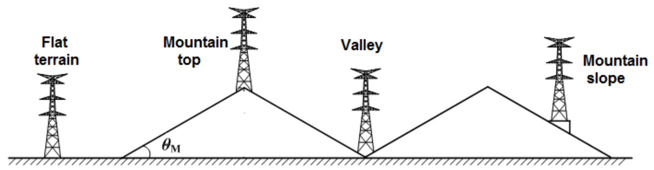

Figure 4. Studied transverse terrain profiles

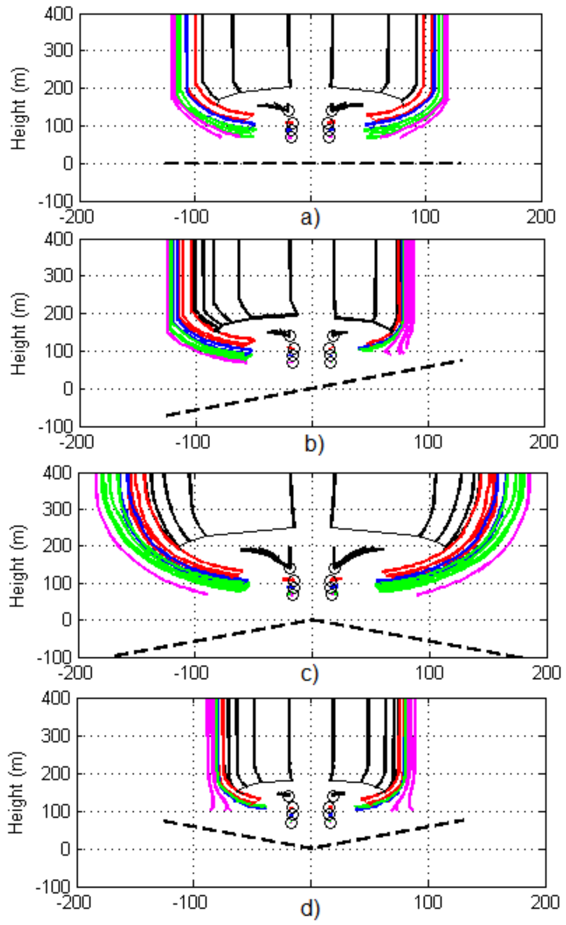

Figure 5. Downward leader paths for a Japanese UHVAC transmission line over a) Flat terrain b) Mountain slope c) Mountain top d) Valley.

Fig. 5 shows the downward leader trajectories and the exposure arcs for the analyzed transverse profiles, considering a terrain slope angle θM of 30°.

The profile mountain slope (Fig. 5b) leads to asymmetric downward leader trajectories and exposure arcs with respect to the line center, getting larger exposure widths for the taller conductors.

On the other hand, the profile mountain top (Fig. 5c) leads to the largest exposure widths. Notice that the corresponding upward leaders are longer than those of the other profiles, which is related to a higher electric field near to the transmission lines due to the mountain top terrain.

Finally, laying transmission lines along a valley (Fig. 5d) has an opposite effect to that of the mountain top. The related exposure widths are shorter than those of the other profiles. This is related to an electric field shielding produced by this profile.

To quantify the influence of these profiles on the shielding performance, the shielding failure ratio (SFR) is computed as proportional to the ratio between the shielding failure half width (SFHW) and the total width of lightning impacts to the transmission line (SFHW+SSHW), that is:

$$SFR = \frac{SFHW}{SFHW + SSHW}$$

Fig. 6 shows the shielding failure ratio as a function of the terrain slope for the previously studied transverse profiles. Clearly, laying a transmission line over mountain tops leads to more number of shielding failures. On the other hand, for a valley profile, the higher the mountain slope, the lower the shielding failure ratio. As for the mountain slope profile, it presents a good performance, leading to a lower shielding failure ratio under an increasing mountain slope.

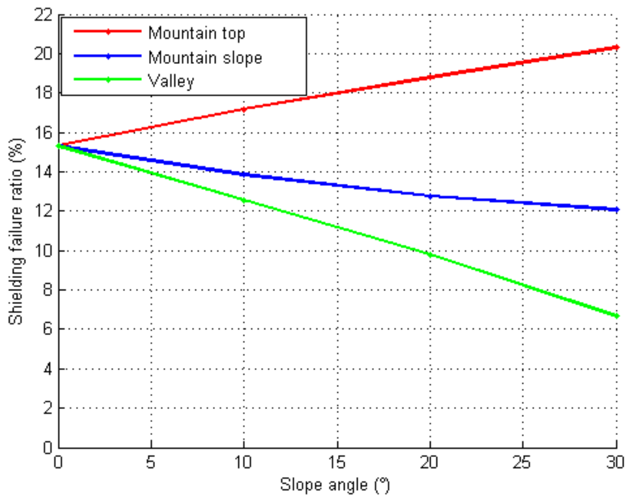

Figure 6. Shielding failure ratio for the Japanese UHVAC transmission line over three transverse terrain profiles as a function of the mountain slope angle

B. *Longitudinal Profiles*

Longitudinal profiles lead to changes in the effective conductor's height along the transmission lines, due to the terrain topography and the transmission line sag. For an analysis using SLIM, it is necessary to simulate descending leaders for multiple coordinates over the transmission line as shown in Fig. 7. In order to reduce the simulation time, a UHVDC transmission line is studied, whose dimensions are shown in Fig. 3b. It corresponds to a negative shielding angle configuration. The DC conductors are simulated at zero potential. A prospective return stroke current of 14.7 kA is considered.

Three typical longitudinal terrains are studied: Inclined, valley and mountainous terrain.

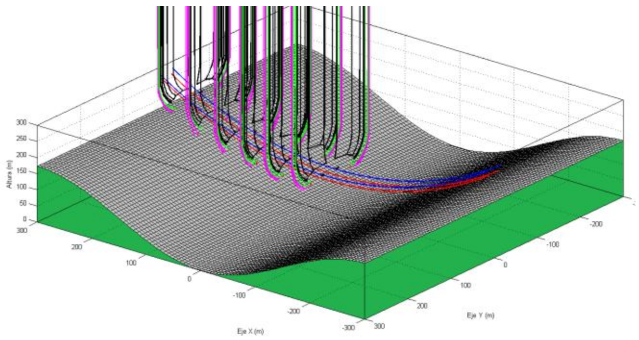

Figure 7. Simulation of multiple downward leaders approaching a UHVDC transmission line along a complex terrain

Fig. 8 shows the exposure areas for the transmission line along an inclined terrain. Since it has been considered the line sag, the conductor's height changes along the line. The top view in Fig. 8b shows that the shielding failure width increases when the effective conductor's height increases. The same effect is observed in Fig. 9, corresponding to the exposure areas for a transmission line built along a valley and a mountain. In this case, the effect of the longitudinal valley, unlike the transverse valley, is negative since it leads to taller conductors and therefore, to larger shielding failure widths.

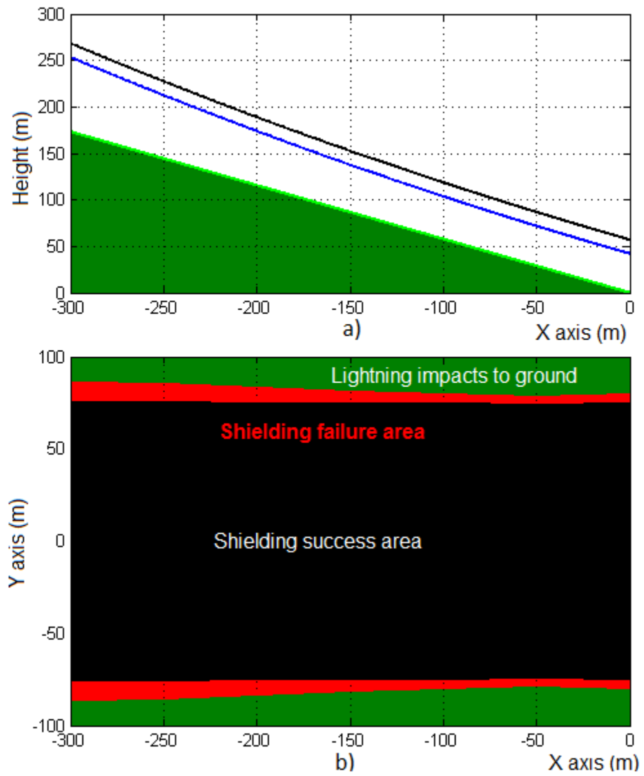

Figure 8. Side view of an UHVDC transmission line along an inclined terrain b) Top view of the corresponding shielding areas

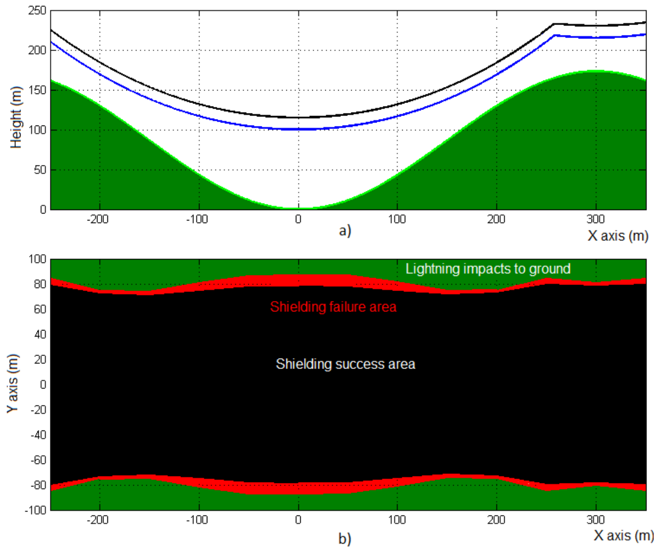

Figure 9. Side view of an UHVDC transmission line along a valley and mountainous terrain b) Top view of the corresponding shielding areas

To evaluate how the shielding failure ratio changes as the conductors height increases, the studied transmission line is simulated at multiple heights over a flat terrain. A constant vertical distance of 15 m between the DC conductors and the shield wires is considered. Fig. 10a shows an increasing lateral distance as the conductor's height increases. It can be seen that for a shield wire height less or equal than 55 m, no shielding failures happen. From this height, an increasing shielding failure width is obtained. Notice that even when the shielding success width increases (black line), the shielding failure width increases more strongly due to a reducing earth shielding effect as the height increases. For this case, the shielding failure ratio varies from 0% up to 4% when the transmission line changes in height from 55 m up to 115 m (Fig. 10b).

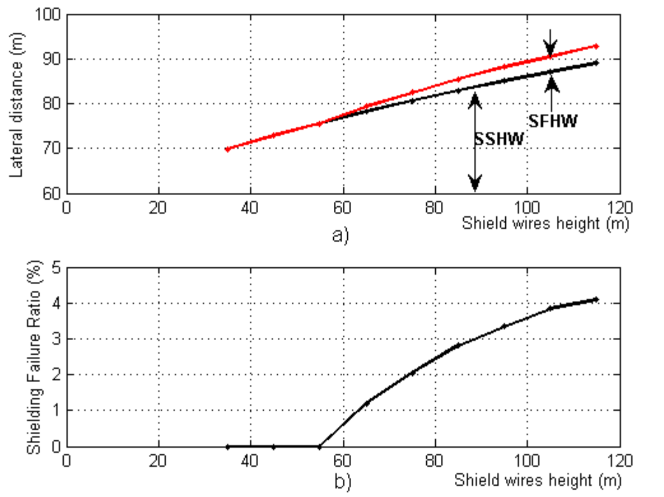

Figure 10. a) Shielding widths for an UHVDC transmission line as a function of the conductors' height b) The corresponding shielding failure ratio

On the other hand, it is evaluated how the striking distance to the conductors changes as their effective height increases. Fig. 11 shows the corresponding striking distance to both shield wires and DC conductors. It can be seen that these distances increase as the conductors' height increases. In addition, the striking distance to the DC conductors is shorter than that of the shield wires, keeping a ratio of about 0.75. It is noteworthy that the obtained ratio for the Japanese UHVAC transmission line, studied in the previous section, was 0.6, which suggests that this relation strongly depends on the tower geometry. These results differ from the EGM, which considers equal striking distances for the DC conductors and shield wires, neglecting the influence of the terrain topography or the conductors' height.

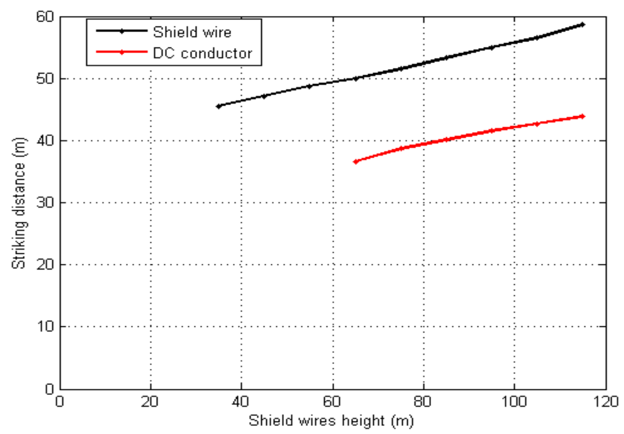

Figure 11. Striking distance to the shield wires and to the DC conductors as a function of the conductors' height

IV. CONCLUSION

SLIM has been improved to analyze the shielding performance of transmission lines. The new downward leader propagation model explains better the direct impacts to the phase conductors, taken into account the electric field distortion produced by the energized transmission lines. From multiple simulations, geometrical factors can be calculated in order to develop a complete analysis of shielding performance, considering critical factors such as the towers geometry, the phase potential and the terrain topography.

The effect of terrain topography on the shielding performance of transmission lines was analyzed. Transverse and longitudinal profiles were considered in an independent way. It was found that the mountain top is the most critical transverse profile, since it increases the lightning attractiveness of the line, leading to larger exposure widths than other profiles. On the other hand, the valley profile produces a shielding effect, reducing the exposure areas of the line. As for the longitudinal profiles, the relative increase of the conductor's height with respect to the earth surface can be critical. For instance, the conductor's height of a transmission line passing over a valley increases, becoming more vulnerable to be struck by lightning impacts.

The striking distance strongly depends on the terrain topography and the tower geometry. It cannot be considered that it is constant and equal to all conductors as it is suggested by the EGM.

Although the presented simulation results are obtained for a constant lightning return stroke peak current, it provides a clear assessment about the effect of the terrain topography on the lightning shielding performance of transmission lines. In future works a statistical analysis could be performed considering the lightning current distribution and calculating shielding performance indicators as lightning trip out rates.

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