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On the interception of lightning flashes by power transmission lines

Liliana Arevalo*, Vernon Cooray

Division for Electricity and Lightning Research, Department of Engineering Sciences, Ångström Laboratory, Uppsala University, Box 534, SE-751 21 Uppsala, Uppland, Sweden

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ABSTRACT

The design of the lightning protection system LPS of transmission lines is based on the well known electro-geometrical model. The electro-geometrical model assumes that the first point on a power transmission line that will come within striking distance of the tip of a down-coming stepped leader channel is the strike point of the lightning flash. The model neglects almost all of the physics associated with the lightning attachment.

Nowadays, as it is possible to use modern hardware and software tools and several different numerical methods, it is feasible to apply the physics of the discharge process to the study of lightning attachment. Such models take into account the movement of the downward and the resulting upward leaders from different points on the structures under consideration.

In this paper, a procedure based on lightning physics was used to analyze the lightning attachment phenomena in EHV transmission lines of 230 kV and 500 kV and the results were compared with the predictions of the electro-geometrical method.

1. Introduction

The design of HV power lines ought to be designed in such a way that the lines should withstand overvoltages and be able to transmit electric power continuously without causing outages or damage to equipment. To meet this requirement, the length of the insulators and the minimum clearance distances of air should be determined and then respected. According to the International Standards [1], the insulation level of a power line is based on the average maximum amplitudes of possible internal overvoltages, such as switching impulses, and low frequency overvoltages. To protect power lines against external overvoltages such as lightning discharges, it is necessary to use shielding screens. The basic idea of the shielding screen is to create a protection for the conductors in the power line. Nowadays, this procedure is suggested in Standards as an effective protection against lightning strikes [2,3].

The foundations for the electro-geometric method are based on concepts developed by a number of scientists, such as Golde [4], Wagner and Hileman [5], Armstrong and Whitehead [6]. The method essentially depends upon the concept of a lightning striking distance D, and on the functional relationship between this striking distance and the amplitude of the crest of the return stroke current, I [7]. The design of the lightning protection for a transmission line is practically independent of the operating voltage, with the main consideration being to obtain the correct protection level by estimating the maximal lightning current amplitude adequately.

The analysis presented here considers four different structures and takes them into consideration along with their shielding wires. All four structures are towers, with the first two being for 500 kV power lines and the other two for 230 kV power lines. For both voltage levels, one tower corresponds to a type of line P-double circuit tower and the other is a line S-single circuit tower.

The towers were selected on the basis of reported lightning associated failures published by the Hydro-Electric Power Commission of Ontario, Canada, and reported in the review of L. Lishchyna [8]. According to the reported data, 230 kV single circuit and double circuit lightning failures, most of the failures in the double circuit structures are due to backflash, i.e. direct strikes to the tower or the shielding wire, and, for the single circuit configuration, shielding failure is the most common cause, attributable to lightning striking the phase conductor.

The effective electro-geometrical method [10,11] and the perfect shielding concept [8,12] were applied to determine the angle of protection of the shielding wire. The basic idea is that the volume protected by the wire is defined by the composition of the volume protected by the virtual vertical rods with vertices on the wire.

The results for the theoretical consideration of the leader inception and the attachment obtained with the electro-geometrical method are compared with the application of the physical

* Corresponding author. Tel.: +46 738457810.
E-mail address: liliana.arevalo@angstrom.uu.se (L. Arevalo).

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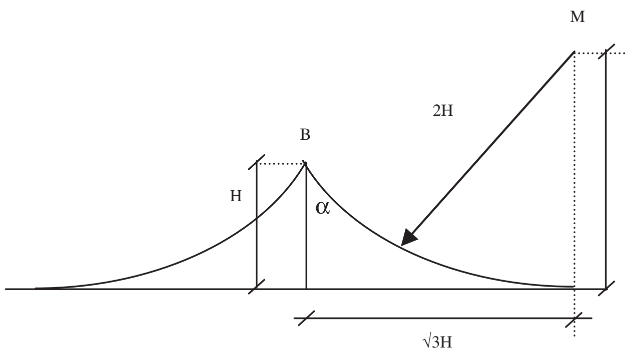

Fig. 1. Protection zone given by a shielding wire in a structure of height *H*. The angle of protection is identified by the letter α.

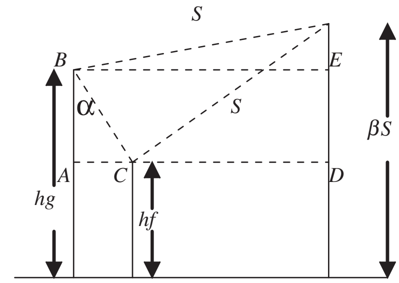

Fig. 2. Protection angle design. *S* corresponds to the striking distance, h_g is the height of the shielding wire above the ground and h_f is the height of the conductor wire above the ground. β is the factor function for the return stroke current [16].

procedure for the four different cases. Not surprisingly, the results show that the connection between the downward-coming leader and the incepted upward-going leader is generated at the point where the shielding wire is supported. Although upward leaders are initiated and propagated from the points where the conductors are supported, no connections were made with downward-coming leader.

2. Application of the electro-geometrical method to the structure

The shielding wire of a power line should be located in such a way that it reduces the risk of lightning related failure considerably. The correct location of the wire is obtained by applying the method known as the "electro-geometrical method" [8,12], according to which, the shielding wire should be positioned in such a way that all parts of the structure to be protected are inside the protection volume defined by the shielding wire [11]. As shown in Fig. 1, this volume is determined by the angle of protection, denoted α.

The striking distance, as defined in the electro-geometrical method, is the minimum distance between the tip of the down-coming leader and the nearest grounded point of the structure. This makes it possible to establish the 'final jump condition' between the stepped leader and the grounded point.

Once the final jump condition is attained, the flash will terminate on the grounded point. This means that the downward leader will impact on the wire, or, if it comes within striking distance of the conductors, it will impact on the conductors.

The striking distance depends on the geometry and on the direct lightning current. In practical applications of these concepts, and based upon experience, several authors have suggested that one made use of the following relationship between the striking distance to ground and the peak return stroke current [4,8,9]:

$$S = A \cdot I_p^b \text{ [m]} \tag{1}$$

Where S is the striking distance in meters, I the peak lightning current in kA and A and b are constants that can have different values depending on the study under consideration [4–11].

According to IEEE [11] A and b have values of 8 and 0.65 respectively, therefore the empirical formula for the striking distance is given by:

$$S = 8 \cdot I_p^{0.65} \text{ [m]} \tag{2}$$

A current of 30 kA, corresponds to a typical first stroke current [13] was assumed for the calculation of the striking distance. Thus, using Eq. (2), incorporating the IEEE recommendations for the coefficients, the striking distance is 72.98 m, however if one uses the criteria defined by others [5–10] it varies between 50 and 150 m. This range agrees with [14] and is consistent with the typical distances observed by Uman [15].

Initially, the design of the shielding wire was based on the models of [4,5] which are pertinent to the protection of a single circuit horizontal configuration, but failures on lines of 345 kV were observed, as reported by [8]. For this reason, an alternative, the "effective shielding protection method" was proposed by Armstrong et al. [6] and Brown et al. [8], and later modified by Eriksson [12].

The design of effective geometrical shielding [12] based on the magnitude of the current, the height of the conductor h_f and the height of the shielding wire h_g involves a calculation of the horizontal distance between both wires and their protection angle as displayed in Fig. 2.

The calculations of the angle of protection are based on the following equations and, in Table 1, results pertinent to the four towers used in the study are summarized:

$$\begin{aligned} k_1 &= \frac{h_g}{S} \\ k_2 &= \frac{h_f}{S} \\ \frac{x}{S} &= \sqrt{1-(\beta-k_1)^2} - \sqrt{1-(\beta-k_2)^2} \\ \alpha &= \arctan\left(\frac{x}{h_g-h_f}\right) \end{aligned} \tag{3}$$

The appropriate value for the factor β was selected from EPRI [16], which incorporates the data published in Ref. [17], and was chosen for the appropriate high voltage level. For currents lower than 50 kA, the magnitude of β is lower than 0.3, which is the value used in the calculation.

Table 1
Shielding angle for the simulated towers.

Circuit characteristic	230 kV double circuit	230 kV horizontal distribution	500 kV double circuit (external phases)	500 kV single circuit
Shielding wire height h_g [m]	44.85	20	69.1	40.36
Conductor wire height h_f [m]	40	17	51.95	33.5
Angle α	16.34	2.6	32	11.9

Shielding angle calculation using Eq. (3), for every circuit the characteristics of the shielding wire and the conductor are given.