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Analysis of shielding failure parameters of high voltage direct current transmission lines

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ABSTRACT

This paper studies the influence of different parameters on the shielding failure of high voltage direct current (HVDC) transmission lines. A numerical analysis model considering the developing process of the downward lightning leader based on electromagnetic field theory is used to estimate the lateral striking distance to the transmission line. The influences of different factors (different parameters of the downward lightning leader, HVDC transmission line, and weather conditions) on the shielding failure of the HVDC transmission line (TL) have been considered in this analysis. The results show that the dimensions of the transmission line strongly affect the analysed results of the HVDC–TL shielding failure.

1. Introduction

A shielding failure is the occurrence of a lightning stroke that bypasses the overhead ground wires and terminates on the phase conductors. Correct design to improve the shielding effect of transmission lines to lightning is one of the key problems of transmission line design.

The study of shielding failures of transmission lines was started by Wagner et al. in 1940s. They developed a study method for shielding power lines and substations based on applying impulse flashovers to reduced scale models [1], but it was invalid when it was applied to the 345 kV North America transmission system built in the middle of 1950's [2].

The electrogeometric model (EGM) was proposed in 1945, but it was not used for shielding failure [3]. It was first used for shielding failure analysis of 345 kV transmission systems instead of the Wagner method in 1950 [4]. Many researchers have studied and applied it to power systems. Wagner et al., [5–7], Young et al., [8], Armstrong and Whitehead [9], Brown and Whitehead [10], Love [11], and Mousa [12–14], have contributed to the EGM.

The EGM defines the striking distance of the stepped leader to an object as a function of the lightning leader current I in kA as [15,16]:

$$r_s = aI^b, \tag{1}$$

where a and b are empirical constants. Different researchers had provided different values of a and b.

Some research work tried to consider the influence of certain parameters on the EGM of the transmission line, the conductor sag [14], the conductor height [17–19] ground slope [20], the wind effect [21].

Fig. 1 shows an EGM of power conductor shielded by a shielding wire at positive shielding angle for a specific lightning stroke current. Arcs of circle with the radii r_c and r_{sw} are drawn, and centred at the power conductor and the shielding wire positions. The ground effects are drawn as a horizontal line at a height r_g parallel to the ground. If the downward lightning leader touches the arc between A and B, then the leader will strike the power conductors. If the leader touches between B and C, then it will strike the shield wire. As all leaders are considered vertical, the exposure

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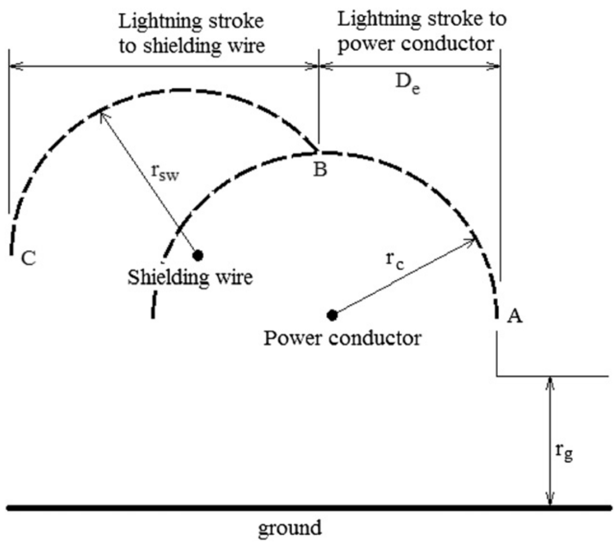

Fig. 1. Electrogeometric model.

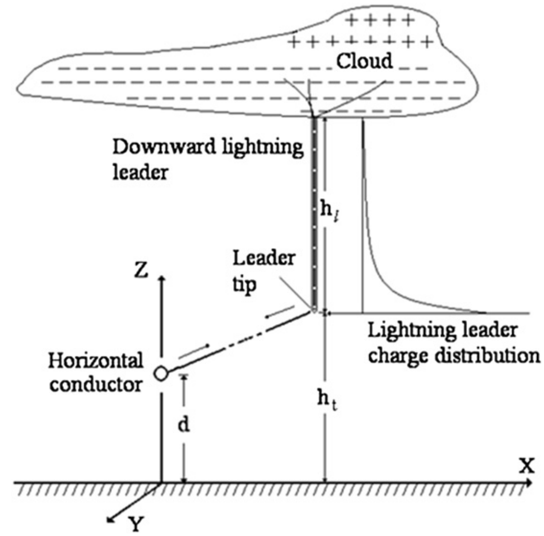

Fig. 2. Schematic arrangement of a horizontal conductor stroked by the downward lightning leader.

distance for a shielding failure is D_c [15,16]. In the two conductor case shown in Fig. 1, there would be a shielding failure rate in one side of $N_g \times D_c \times L$ (lightning strokes number), for a specific lightning current, line of length L, and ground flash density N_g.

Another method to calculate the shielding failure probability was based on various proposed formulae according to actual operation experiences of transmission lines [22–25]. These formulaeformulae are obtained from statistical results of actual terrain of the transmission lines used for the statistical analysis, so using these formulae to analyse other transmission lines is not appropriate.

A numerical analysis method was adopted [26] for shielding failure analysis of the transmission line based on electromagnetic field theory. The electric field of the system including lightning leader, transmission line, and ground was solved, the range of lightning current striking the phase conductor is obtained, and the shielding failure probability of transmission line is calculated. A dynamic simulation was proposed [27] to account the strikes to towers, phase wires, ground wires and earth.

Leader progress model LPM was assumed and showed a very good improvement on the analysis of lightning shielding failure for high voltage direct current transmission lines [28–30].

This paper will improve the EGM by using an electromagnetic model to calculate the lightning stroke distance directly. The influence of different parameters like conductor radius, humidity, air density, wind, and lightning leader parameters (lightning leader charge density distribution and lightning leader length) are consider in estimating the lightning stroke distance. The influences of different parameters of lightning (lightning leader charge density distribution and lightning leader length), high voltage direct current (HVDC) transmission line, and ambient are studied regarding the shielding failure rate of HVDC transmission lines.

2. Modified electrogeometric model

2.1. Electromagnetic model

Consider a horizontal conductor at height h exposed to a downward lightning leader, as shown in Fig. 2. An electromagnetic model has been constructed to estimate the lightning stroke distance to the horizontal conductor [31].

In this paper, the charge decaying distribution along the stepped leader is assumed to be exponential and of negative charge as [32]:

$$\rho(z) = \rho_t e^{-\alpha(z-h_t)} \quad \alpha = \frac{\ln(\rho_c/\rho_t)}{(h_c-h_t)}, \tag{2}$$

where, ρ_t is the charge density (C/m) at the tip of leader stroke ($z = h_t$), ρ_c is the charge density (C/m) at cloud base ($z = h_c$), h_c is the cloud height above ground (m), and h_t is the height of the leader stroke tip above ground (m).

The downward lightning leader length h_l is assumed to be constant and equal to 3 km, and $\rho_c/\rho_t = 0.05$. This value results in $\alpha = 10^{-3}$. The downward lightning leader is simulated by n discrete line charges along the positive Z direction.

The downward lightning leader is simulated by N_ℓ vertical discrete constant charge densities in the Z direction. The charge density for the n segment at z_{nl} from $z = h_t$ to $z = h_c$ will be as follows:

$$\rho_{nl} = \frac{\rho_t e^{\alpha h_t}}{-\alpha|z_{nl-1} - z_{nl}|}\left(e^{-\alpha z_{nl-1}} - e^{-\alpha z_{nl}}\right), \tag{3}$$

The potential of the downward lightning leader at any point in the space is expressed as:

$$V_l = \sum_{nl=1}^{N_l} P_{nl}\rho_{nl}, \tag{4}$$

where $P_{n\ell}$ is the potential coefficient for the n_ℓth vertical discrete constant charge density (see Appendix I).

The formula proposed by Rizk [19] to estimate the voltage at the centre of a horizontal conductor due to the presence of lightning leader is chosen to be the base for investigating a lightning stroke to a horizontal conductor. Fig. 3 shows the scattering plot of calculated striking distance by using Eriksson equation [17,18] and those calculated by using LPM and Rizk conditions. The main deviation between Eriksson equation and results based on Rizk condition is 20%. The main deviation between Eriksson equation and results based on LPM model is 12%. The lightning striking distance based on Rizk conditions are longer than those obtained from Eriksson equation and LPM, as shown in Fig. 3, and this shows good reliability for calculating shielding failure. Fig. 4 shows the distribution of electric field around a horizontal conductor due to a presence of