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Probabilistic evaluation of lightning performance of overhead transmission lines, considering non-vertical strokes

A. Shafaei [a,*], **A. Gholami** [a], **R. Shariatinasab** [b]

[a] *Department of Electrical Engineering, Iran University of Science and Technology, Tehran, Postal Code: 16846-1311, Iran*
[b] *Power System Group, Faculty of Engineering, University of Birjand, Birjand, P.O. Box number: 97175-376, Iran*

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Abstract This paper represents a developed procedure for the evaluation of flashover rates caused by both lightning vertical and non-vertical strokes on transmission lines, using a Monte Carlo method. The main goal of this paper is to increase the accuracy flashover rates through the accurate modelling of network components, such as footing impedance, the transmission tower and chain of insulators, and also simulation of lightning non-vertical strokes. Modelling network components, statistical parameters related to lightning and a problem-solving algorithm are described. Parametric studies using this procedure can also be performed to determine the sensitivity of the flashover rate with respect to some parameters of the return stroke and the transmission line. Simulation results obtained using MATLAB and the ATP/EMTP show that considering the lightning non-vertical instead of vertical strokes leads to a better evaluation of the lightning performance of transmission lines.

1. Introduction

Theflashover caused by lightning strokes has been one of the greatest factors seriously affecting the reliability of HV overhead transmission lines. The lightning performance of an overhead transmission line can be measured by the flashover rate, usually expressed as the number of flashovers per 100 km and year. Due to the random nature of lightning, calculations must be based on a statistical approach. A Monte Carlo simulation is a very common method for this purpose [1–3].

Usually, transmission line protection against lightning strokes is achieved by means of ground wires. However, especially in regions with high ground resistance, there is a high probability of failure of the insulation following a Back Flashover (BF). Furthermore, there is a probability of shielding failure, which can lead to a flashover (SF). Hence, the lightning flashover rate (LFOR) of a transmission line is equal to both Back Flashover Rate (BFR) and the flashover rate due to shielding failure (SFFOR). To obtain both quantities, an incidence model is required to discriminate strokes to shield wires from those to-phase conductors and those to-ground [4,5].

A Monte Carlo procedure for studying lightning stress can consist of the following steps [6,7]: the generation of random numbers to obtain those parameters of the lightning stroke and the overhead line of a random nature; application of an incidence model to determine the point of impact of every lightning stroke; calculation of the overvoltage generated by each stroke, depending on the point of impact; and calculation of the flashover rate.

In this paper, statistical methods to evaluate the lightning performance and calculation of flashover rates, both vertical and non-vertical strokes, are implemented. The developed method has been coded in MATLAB and linked to an EMTP/ATP draw program to perform network simulations directly. Since the collection of statistical data from networks with detailed modeling of their elements is possible, a transmission tower is represented by a multistory model [8], the representation of insulator strings is based on the Leader Progression Model

* Correspondence to: No 2/2, First Floor, Golsar Alley, Mahdieh St., 15 Khordad Ave., Sari, Mazandaran, Postal code: 48188-57349, Iran. Tel.: +98 09195852825; fax: +98 2177240490.
E-mail addresses: amir.shafaei87@gmail.com (A. Shafaei), gholami@iust.ac.ir (A. Gholami), Shariatinasab@ieee.org (R. Shariatinasab).
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Table 1: Statistical parameters of return strokes.

Parameter	x	$\sigma_{\ln x}$
I_p (kA)	34	0.74
T_r (μs)	2	0.4943
T_t (μs)	77.5	0.577

(LPM) [9] and footing impedance is represented as a nonlinear current-dependant resistance [10,11].

The rest of the paper is organized as follows. Section 2 describes the characteristics of return stroke parameters and their statistical distribution. Section 3 gives a summary of methods developed to determine the impact of lightning, vertical and non-vertical, strokes. Some important aspects of the Monte Carlo procedure are summarized in Section 4. A summary of modeling guidelines is presented in Section 5. In Section 6, we present and discuss results obtained from the simulation. A parametric study of the test line, aimed at determining the relationship of the flashover rate, with respect to some parameters of the transmission line and some variables of the return stroke current, are detailed in Section 7, and, in Section 8, we conclude this paper.

2. Lightning parameters

Frequently, both the double exponential and triangular waveforms have been used to represent lightning return stroke currents. Presently, it is assumed that a concave waveform of the first stroke, as shown in Figure 1, is a better representation, since it does not show a discontinuity at $t = 0$ [6]. Several expressions have been proposed for such a waveform, and one of the most widely used is the so-called Heilder model given in [5,12]

$$i(t) = \frac{I_p}{\eta}\frac{k^n}{1+k^n}e^{-t/\tau_2}, \tag{1}$$

where I_p is the peak current, η is a correction factor of the peak current, n is the current steepness factor with $k = t/\tau_1$, and τ_1 and τ_2 are time constants determining current rise and decay times, respectively. The main parameters used to define this waveform in the present work are the peak current magnitude, I_{100}, the rise time, $T_r[= 1.67(t_{90} - t_{30})]$, and the time to half value, Tt. In this work, only negative strokes have been considered. Table 1 shows the parameters of the log-normal distribution [13].

3. Determination the point of impact for non-vertical strokes

To determine the point of impact for non-vertical strokes, characteristics of the area of impact are determined by assuming uniform distribution. Then, the angle of impact is obtained randomly. Finally, the point of impact is determined by the Electro Geometric Model (EGM).

3.1. Area of impact

To determine the area of impact, regardless of strike distances, the length and width point of the stroke must be acquired as uniformly distributed over a specific area. The area where the lightning strokes are located is shown in Figure 2 [7]. The width of d must be calculated, corresponding to the

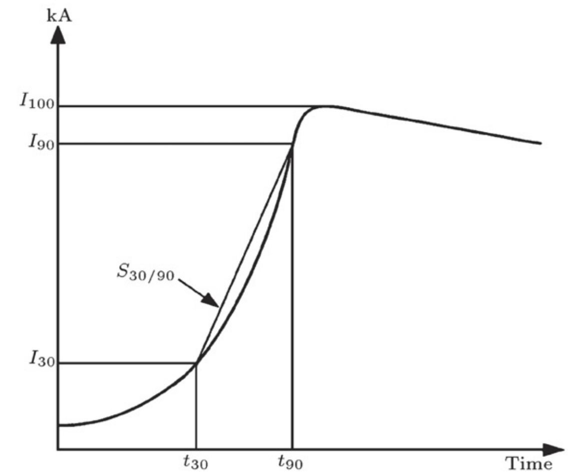

Figure 1: Typical return stroke waveform of lightning current.

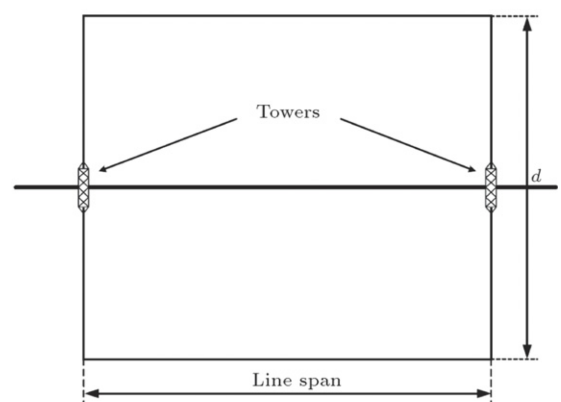

Figure 2: Area of impacts.

maximum peak current magnitude, as derived from application of the electro geometric model [14].

The maximum peak current magnitude generated in the simulation was about 400 kA, so the maximum distance should be about 500 m, as used in this work.

3.2. Distribution of stroke angle

In most studies, lightning strokes are considered vertical, while usually hitting the ground non-vertically. Also, the angles of a stroke show a random behavior that can be displayed with a probability density function by Eq. (2) [7,15]:

$$p(\psi) = \begin{cases} 0 & \psi < -\pi/2 \\ k\cos^m\psi & -\pi/2 < \psi < \pi/2 \\ 0 & \psi > \pi/2 \end{cases} \tag{2}$$

where ψ is the angle deviation from the vertical direction, and m is a constant exponent. Also, $p(\psi)$ is defined by Eq. (3) [7]:

$$p(\psi) = \int_{-\pi/2}^{\pi/2} k\cos^m\psi.d\psi = 1. \tag{3}$$

Consequently, the k factor, based on different values of m, is calculated as follows [7]:

$$k = \frac{1}{\int_{-\pi/2}^{\pi/2}\cos^m\psi.d\psi}. \tag{4}$$