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3D computer graphics enhanced shielding failure evaluation by collection surface method

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ABSTRACT

A new lightning shielding failure evaluation method based on the electro-geometric method aided by 3D graphics technology is introduced. The approach is based on the collection surface method. Shielding devices and protected equipment are equally considered as targets of lightning strikes when generating collection surfaces. The collection surfaces are then projected to a 2D bitmap, identified by colors to represent protected and unprotected areas respectively. An integral is performed on the amplitude of the stroke current (weighted by the probability distribution of this amplitude) to account for the dependency of the shape and size of the unprotected surface on the stroke current. By using the collection surfaces of equipment instead of the unprotected area, empty areas where no equipment is to be protected are eliminated from contributing to the failure analysis. The technique applies to structures or substations of any shape, and can use different striking distances to horizontal and vertical objects. The example 69 kV substation described in IEEE Standard 998 is used to demonstrate the usage of this technique.

1. Introduction

Shielding failure analysis helps engineers quantify the effectiveness of a lightning protection system against direct lightning strikes. In practice, the system of interest may not be fully protected against direct lightning strikes for technical or economic reasons. In such cases, the designer has to determine the risk level to which the installation is exposed, based on safety and reliability requirements. Shielding failure analysis may provide valuable information in this risk determination process.

Shielding failure is the occurrence of lightning strikes terminating on the system to be protected, bypassing the protection devices. It is a function of the preponderance of lightning activity at the location of the installation – which is obtained empirically – and of the surface area of the installation where equipment is exposed to lightning strikes. This last quantity is a complicated function of the geometry of the equipment and of the shielding devices, and varies according to the magnitude of the stroke current. Its determination is not straightforward, and is often subjected to coarse approximations.

The Rolling Sphere Method (RSM) derived from Electrogeometric Method (EGM) and suggested by IEEE Std 998 [1] is among the most widely adopted methods for shielding analysis. However, the application of RSM requires complex geometrical calculations. Several numerical techniques have been proposed to carry out this procedure. Some of them are based on analytical solutions, but are restricted to a small set of special geometries [2]. Others use 3D technologies to build a structure model and simulate the process of rolling an imaginary sphere over the structures in the model, which results in a very time-consuming process for complex structures.

The collection surface method (CSM) is an alternative to the RSM [3]. Aided by 3D graphics technology [4], this method applies to structures or substations of any shape. It can use different striking distances to horizontal and vertical objects and yields accurate calculations of exposed area to lightning strikes.

Collection surfaces are generated for both shielding devices and equipment; the portions of the collection surfaces of equipment that are not covered by the collection surfaces of shielding devices are considered exposed to lightning, and are tallied up in the shielding failure analysis. By using the collection surfaces of exposed equipment instead of that of the unprotected area of the whole system, empty areas where no equipment is present are eliminated from contributing to the shielding failure rate.

The collection surfaces are projected to a 2D bitmap, using different colors to identify the protected and unprotected areas. This projection is carried out and achieved effectively using standard capabilities of 3D graphics cards. An integral is performed on the

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0378-7796/

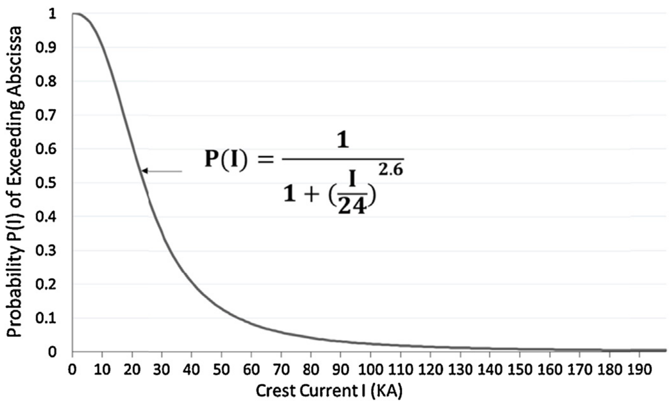

Fig. 1. Probability of first negative return stroke peak current exceeding abscissa for strokes to flat ground [1].

amplitude of the stroke current (weighted by the probability distribution of this amplitude) to account for the dependency of the shape and size of the unprotected surface on the stroke current.

The following sections give more details on this method. The example of the 69 kV substation described in IEEE Standard 998 is used to demonstrate the application of the proposed method.

2. Calculation of shielding failure rate

2.1. Theoretical formulation

The average number of lightning strokes per unit area per unit time at a particular location is defined as the Ground Flash Density (GFD). The GFD is roughly proportional to the keraunic level at the location; it is calculated using [1].

$$N_k = 0.12 T_d \tag{1}$$

where N_k is the GFD expressed as the number of flashes to earth per square kilometer per year and T_d is the keraunic level, in thunderstorm days per year.

The average annual number of flashes X_k in a given area is calculated using the following equation:

$$X_k = N_k \times A \tag{2}$$

where A is the area in square kilometers.

Not all the flashes are contributing to shielding failure: only those for which the stroke current exceeds the equipment withstanding current will cause damage. The probability that a certain current will be exceeded in a strike is calculated using the following equation:

$$P(I) = \frac{1}{1 + \left(I/I_M\right)^{\alpha}} \tag{3}$$

where $P(I)$ is the probability that a current I (in kilo-amperes) is exceeded by the peak current in a strike, I_M is the median of the current distribution and α is an exponent, typically set to 2.6. Fig. 1 shows a plot of (3) for $I_M = 24$ kA, commonly used for substations [1].

The shielding failure rate (SFR) X of a partially protected system is defined as the number of flashes terminating inside the unprotected area of the system which will cause equipment damage and failure, within a given period of time (generally one year). It is given by:

$$X = -\frac{\int_0^{\infty} \mathrm{d}P(I)}{\mathrm{d}I \times N_k \times A(I)\,\mathrm{d}I} \tag{4}$$

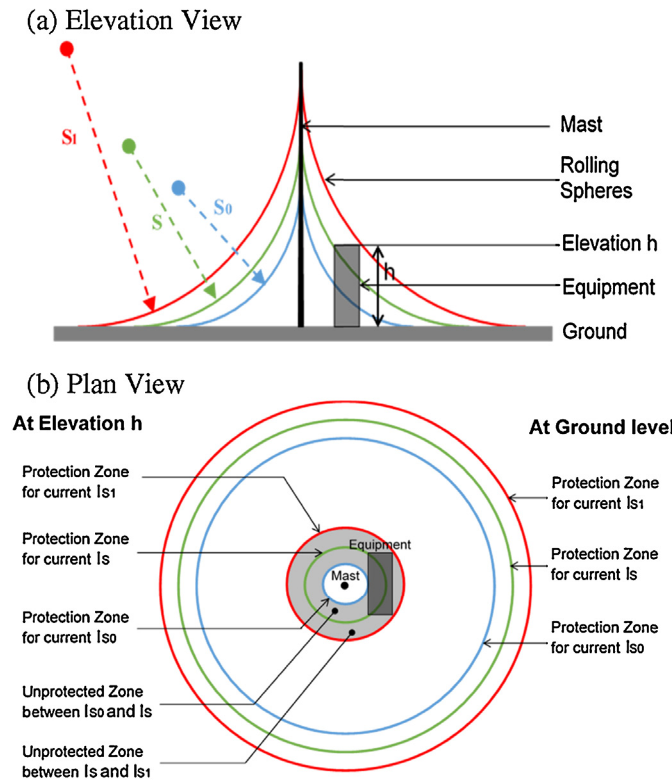

Fig. 2. Unprotected area of shield mast for stroke currents I_{s0} and I_{s1} using rolling sphere technique. (a) Elevation view of the system and (b) Plan views of the system at ground level and at elevation h.

where $A(I)$ is the unprotected area for a given stroke current I, N_k is the ground flash density and $P(I)$ is the probability that the peak current in a stroke will exceed I. The quantity $\mathrm{d}P(I)/\mathrm{d}I \cdot \mathrm{d}I$ appearing in the integrand represents the probability distribution that the peak current in any stroke will lie between I and $I + \mathrm{d}I$.

The upper bound of the integral can be restricted to the stroke current I_{s1} for which the system is fully protected (which is determined by the characteristics of the protection system), while the lower bound can be restricted to the stroke current I_{s0} that the system can withstand without damages, which is usually defined by the equipment BIL. If a value for I_{s1} cannot be found (meaning that the system can never be fully protected for any stroke current value), the upper bound of the integral is set to a sufficiently large value, so that the contributions to the shielding failure from the stroke currents larger than this value can be safely ignored.

2.2. Approach used in standard

If the variation of the unprotected area $A(I)$ for $I_{s0} < I < I_{s1}$ can be neglected, Eq. (4) can be simplified as:

$$X = (P(I_{s0}) - P(I_{s1})) \times N_k \times A(I_{s0}) \tag{5}$$

Thanks to its simplicity, this approach has been widely applied in shielding failure analysis. One typical application example is illustrated in Fig. 2, adapted from Fig. 27 of IEEE standard 998 [1]. S0, S, and S1 are striking distances corresponding to stroke currents I_{s0}, I and I_{s1}. From part (a) of the figure, it is clear that the equipment is not protected for stroke currents inferior to I_{s1} since the equipment intersects the rolling sphere for any current I smaller than I_{s1}. Part (b) of the figure shows the unprotected area at elevation h for stroke currents between I_{s0} and I_{s1}, corresponding to the shaded area in light gray between the inner blue circle and the inner red