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Calculation of surface electric field on UHV transmission lines under lightning stroke

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ABSTRACT

Lightning is the major cause of interruptions in power transmission lines. Ultra-high voltage (UHV) AC transmission line has been put into operation in China. Due to the large tower height up to 90 m and the high operation voltage up to 1000 kV, the shielding failure probability increase obviously. Nowadays the leader progression model is an advanced method to evaluate the shielding failure probability of transmission lines. The surface electric field is the key issue for lightning failure analyzing, because the upward leader inception mainly depends on the surface electric field. In this paper, the lightning leader model is introduced. A charge simulation method based piecewise linear function is adopted to analyze the surface electric field on phase conductors and ground wires. The influence factors, such as operation voltage, lightning peak current, lightning down leader position, protection angle, on surface electric field were analyzed.

1. Introduction

The shielding failure is the major cause of interruptions in power transmission systems. The rational design to improve the shielding effect of transmission line against lightning is one of the key problems of transmission line design. Now 1000-kV ac ultra-high voltage transmission line has been put into operation in China. The transmission tower reaches about 70–90 m high, and 30–60 m wide, thus, the lightning attraction area of 1000-kV transmission line is much wider. Meanwhile, with the increment of operation voltage of the long-distance transmission lines, proportion of shielding failure rises [1]. Due to the high insulation level of the 1000-kV transmission line, the threaten of direct lightning stroke is very small, but the probability of shielding failure increases obviously due to very high towers.

According to the statistical results of power system failure classification, above 50% of power system failures were caused by lightning in Japan [1]; about 40–70% of the total tripping numbers of transmission lines in high voltage power system were caused by lightning in China [2]. According to the operation experiences of 1150-kV ac transmission lines in Russia, the lightning trip-out rate was 84.4%, its length is 493.2 km. The first double circuit UHV transmission line which has a length of approximate 490 km was completed in Japan in 1999, and it has being operated in 500 kV [3]. Field observation of the characteristics of direct lightning strokes to the double circuit UHV transmission line was carried out by The TEPCO during 1998–2004 [4].

The Electro-geometry Method (EGM) [5–7] treats the lightning strike process as a geometry drawing, the effect of conductor dimension cannot be considered, so for 1000-kV transmission line with the tower height taller than 70 m, this effect would have strong influence on the upward leaders from tower, shield wires and phase conductors, certainly on the downward lightning leader, too.

With the progress of the long air gap discharge research, leader progress model (LPM) has become the new approach to analyze the shielding failure of transmission line. Many researchers had studied LPM [8–11] and proposed different models. LPM considers the variation of space electric field and its effect on the lightning developing progress during the lightning striking the conductor. It is much more approaching to the physics of lightning, is able to overcome the difficulty of EGM.

The LPM proposed a description of the whole developing process of descending leader to upward leader. An assessment model is proposed here in the conception of LPM, based on the lightning survey data and the physics of leader discharge. The LPM is an advanced

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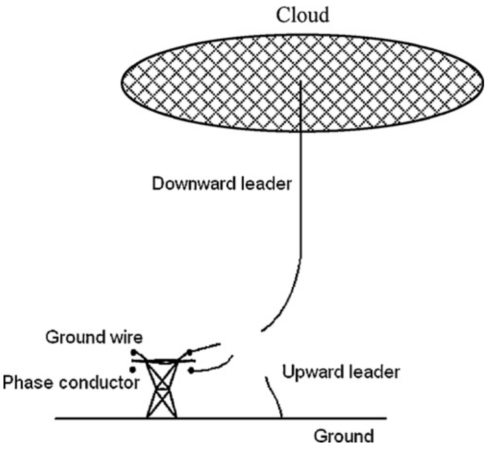

Fig. 1. Lightning leader progress model.

method for evaluating shielding failure probability of transmission lines nowadays.

It is a key issue to calculate the surface electric field on phase conductors and ground wires, because the upward leader inception mainly depends on the surface electric field. The charge simulation method has developed rapidly in the recent years and has emerged as a very efficient and accurate method for electric field calculations [12,13]. In this paper, a charge simulation method based piecewise linear function is applied. The surface electric field on different phase conductors and ground wires is analyzed. The influence of critical radius of a conductor on the surface electric field is taking into account. The influence factors, such as operation voltage, lightning peak current, lightning down leader position, protection angle, on surface electric field were analyzed.

2. Method for surface electric field calculation under lightning stroke

2.1. Method for surface electric field calculation

In the lightning LPM, the downward and upward leader, transmission line and ground are considered as charged structure. The electric fields of these objects are calculated simultaneously. When the surface electric field on an object exceeds the critical value, then an upward leader generates from this object. When the average electric field between the downward leader and upward leader tips exceeds the critical breakdown one, then the downward leader emerges with the upward leader, and lightning strikes this object [5–7]. Fig. 1 shows the lightning leader progress models.

The cloud is represented by a mono-polar surface charge model, the amount of charge is 8 C, and the diameter of the surface is 10 km [8]. For the relationship between lightning peak current I (kA) and total charge Q_c (C) in leader channel, different researchers gave different formulas [8,11,14,15]. Formula in [11] is significant different from others when lightning peak current is large, the others have a good agreement. In this paper, the formula in [8] is used.

$$Q_c = 76 \times 10^{-3} \cdot I^{0.68} \tag{1}$$

Several distributions, such as uniform distribution, linear distribution, and exponential distribution are considered for total charge in lightning channel [3,8,11]. Observations show that the charge density in lightning channel head is quit larger than in other parts. Therefore, one reasonable model is that charge in the lightning channel is considered as uniform distribution, and concentrate charge is used to simulate the head of the lightning channel, the relationship between the concentrate charge and the charge density can be establish by Gauss' law. In this paper, the lightning channel head is considered as a semi-sphere with radius r_s, and the channel is a cylinder with the same radius. Then the concentrate charge in the head and charge density in the channel can be represented as:

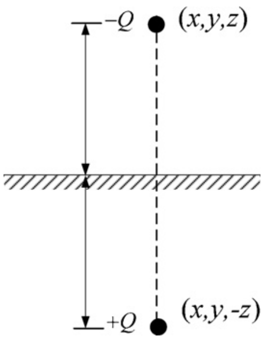

Fig. 2. Image of charge above the ground.

$$q_c = \frac{Q_c}{l} \tag{2}$$

$$Q_h = 2\pi\varepsilon_0 r_s^2 E_s \tag{3}$$

where q_c is the charge density in the lightning channel, C/m. l is the lightning channel length, usually is taken as 2 km. Q_h is the concentrate charge in the head, C. E_s is minimum field strength to keep lightning developing itself in the channel and head. For positive leader, it is 5 kV/cm, for negative leader, it is 10 kV/cm [14]. The radius of the semi-sphere tip of the downward leader r_s (cm) is calculated by [5]

$$r_s = 3.0\log(I + 20) \tag{4}$$

The electric field is treated as electrostatic field or quasi-electrostatic field, when analyzing the lightning strike the objects on the ground. Lightning leader can be simulated by charge source. Therefore, it is easy to get the relationship between the lightning current and total charge in the lightning channel, and is effective on electric field calculation. In this paper, shielding failure of UHVDC is the main key topic, so charge simulation model is applied.

In the charge simulation method, the simulation charges are placed in the central axis of conductors [15,16]. In order to maintain the surface voltage potential of the conductor, charges are induced on the conductor. Every sub-conductor is represented by a linear charge. The ideal ground is represented by image charge underground. As shown in Fig. 2, the image of a point charge $-Q$ located at (x,y,z) is a point charge Q at $(x,y,-z)$.

For bundle conductors and fixed gap length,

$$\mathbf{A}\mathbf{Q} + \mathbf{A}_1\mathbf{Q}_1 = \mathbf{\Phi} \tag{5}$$

where $\mathbf{Q}$ is simulation charge column matrix of sub conductors and images, $\mathbf{Q}_1$ is simulation charge of lightning leaders and their images. $\mathbf{A}$ and $\mathbf{A}_1$ is the corresponding voltage potential coefficient matrix, where is only determined by the positions on sub conductors, lightning leaders and their images. Φ is the voltage potential column matrix on the check points. Then, the simulation charges of the bundle conductors and their mirrors can be calculated as (6). The surface electric field also can be calculated by (7).

$$\mathbf{Q} = \mathbf{A}^{-1}(\mathbf{\Phi} - \mathbf{A}_1\mathbf{Q}_1) \tag{6}$$

$$\mathbf{E} = \mathbf{F}\mathbf{Q} \tag{7}$$

where $\mathbf{F}$ is the electric field coefficient matrix which is determined by the positions of conductors and leaders. $\mathbf{E}$ is the surface electric field vector.

Considering a finite horizontal straight conductor, assume the line charge density as a piece linear function. Set the central axis