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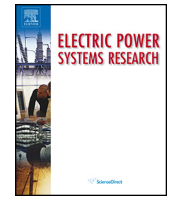

Calculation and experiment of induced lightning overvoltage on power distribution line

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ABSTRACT

Induced lightning is the major cause of interruptions in power distribution lines. To reduce lightning accidents and improve the power supply reliability, it is significant to study the characteristics of the induced lightning overvoltage by experiment and calculation. In the paper, a calculation method of lightning induced overvoltage, considering lightning leader progress, non-ideal ground corona effect, field-line coupling, was introduced. The accuracy of the program was verified by comparison between calculated results and the practical experimental results, the calculation results are close to the experimental data. A scaled experiment was carried out to obtain the basic relationship between lightning and overvoltage on distribution lines. Influence factors on overvoltage were analyzed.

1. Introduction

Lightning is the most important reason of distribution lines fault, especially in severe lightning activity areas [1,2]. There are two different ways leading to outage in distribution line due to lightning overvoltage: lightning strike directly on the distribution lines, and induced overvoltages caused by strikes nearby [1]. Because of the lower insulation withstand level of power distribution lines, induced overvoltages becomes the major cause of the lightning outage. According to the operation experience, up to 90% lightning faults were relative to induced lightning overvoltage. Thus researches on the lightning induced overvoltage of distribution lines are conducive to further understanding of lightning induced overvoltage and the mechanism of its formation and development regularity, which helps to enhance the structure design of distribution overhead lines, enhance the protection and decrease electrical faults caused by lightning induced over-voltage as well as to improve power supply reliability.

In the first half of the 20th century, the most accepted theory for lightning overvoltage was bound charge. The charge of overhead negative clouds induces positive charge on distribution lines. Under the combined effects of negative thunderclouds charge and positive induced charge on the lines, the total potential of lines is zero. When lightning occurs, the charge in clouds is neutralized, the charge of line brings a positive potential to the ground [2]. In later studies, the development of lightning leader was considered as the main course of distribution overvoltage. However, compared to the return stroke, the potential of lightning leader is less. Earlier researches show that the overvoltage caused by the downward stepped lightning leader can probably cause the action of protection device [3].

The modern theory of lightning induced overvoltage describes the progress as follows: first, a lightning channel appears between clouds and ground. When the return stroke happens, return stroke current appears in the channel. Then the current induces space electromagnetic field and the electromagnetic field may induce overvoltages on the lines [1,2,4,5].

To give an accurate analysis of distribution lines lightning induced overvoltage, the main problems to be solved are as follows: lightning current waveform model, lightning return stroke model, electromagnetic field propagation model, and field-line coupling model. In this paper, calculation models and parameters were proposed to calculate lightning induced overvoltage. The results are examined and validated by simulation.

A scaled experiment system was established to obtain basic relationship between lightning and overvoltage on distribution lines, and to verify the calculation method. The scaled experiment is easier to be carried out, and a variety of parameter could be

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Table 1
The values of $P(z)$ and v in various lightning return stroke models.

Model type	$P(z)$	v
TL	1	v_f
MTLL	$1-z/H$	v_f
MTLE	$\exp(-2/\lambda)$	v_f
BG	1	∞
TCS	1	$-c$

controlled. Compared with other tests of the coupling of lightning fields to transmission lines, the leader impact on the lightning induced overvoltage was considered in this paper, and the field strength was measured accurately with photoelectric sensors, which was developed by Tsinghua University advanced power delivery laboratory. At last various influence factors were analyzed.

2. Calculation method of induced lightning overvoltage

2.1. The lightning return stroke model

The calculations of spatial-temporal distribution of return stroke current are generally based on the current on the bottom of lightning channel. The current waveforms of Heidler model and Double exponential model are similar, but difference consists between the differentials of two kinds of waveforms. In general, Heidler model is more in line with the under-standing and expectation of lightning current compared with Double exponential model. Thus, Heidler model is adopted [4]:

$$i_{l0}(t) = \frac{I_{\text{peak}}}{\eta} \exp\left(\frac{-t}{\tau_2}\right) \frac{(t/\tau_1)^n}{\left(1+(t/\tau_1)^n\right)} \tag{1}$$

where, $i_{l0}(t)$ stands for the current on bottom of channel at time t, I_{peak} stands for the peak value of lightning current, τ_1 stands for the constant related to the current front time, τ_2 stands for the parameter related to the rate of decay of lightning current, n stands for the parameter related to the gradient of wave-front. The larger n is, the larger gradient of wave-front is. η can be calculated by the following formula [4]:

$$\eta = \exp\left(\frac{-\tau_1}{\tau_2}\left(\frac{n\tau_2}{\tau_1}\right)^{(1/n+1)}\right) \tag{2}$$

Researchers have proposed several models of lightning return stroke [4,6,7]. Rakov classified these models according to their applications [6]. And in this paper, MTLE model was used. The peak value of lightning current at height z and time t can be expressed as the following formula [6]:

$$i_l(z,t) = u\left(t-\frac{z}{v_f}\right)P(z)i_{l0}\left(t-\frac{z}{v}\right) \tag{3}$$

where z is the height of observation point to the ground, $P(z)$ is a correction parameter related to z, v is the propagation velocity of current in the channel, u stands for Heaviside Function, v_f is the propagation velocity of the return stroke current along the channel. When $t > z/v_f$, $u = 1$, otherwise $u = 0$. The values of $P(z)$ and v are shown in Table 1, in which c is the speed of light and λ is a constant.

$$P(z) = \exp\left(\frac{-z}{\lambda}\right) \tag{4}$$

$$v = v_f \tag{5}$$

The velocity of lightning channel development $v_f = 1.3\text{e}^2\ \text{m}/\mu\text{s}$, and the v_f is equal to v. λ is 2 km in MTLE model.

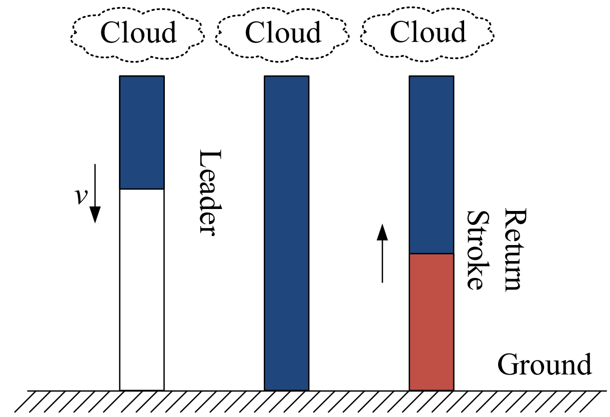

Fig. 1. Leader and return strike progresses.

Leader progress of lightning is not included in the return stroke, but it will affect the induced overvoltages. Therefore, a similar model is used to calculate and describe the development of lightning leader [8]. Shown in Fig. 1, in the thunder cloud, the total charge of cloud is Q, the downward leader develops at a constant speed v. When the leader reaches ground, the return stroke happens rapidly. The density $\rho(z, t)$ of charge in lightning channel is calculated as follows [4].

$$\rho(z,t) = \rho_0 u\left(t-\frac{H-z}{v}\right) - \rho_0 vt\delta(H-z)u(t) \tag{6}$$

where, $\delta(t)$ is Dirac function, its integration is 1 in time domain, and $\delta(t) = 0$ when $t \neq 0$; ρ_0 is a constant of charge density.

The velocity adopted for the downward stepped leader is $v = 0.2\ \text{m}/\mu\text{s}$. The waveform of electric field intensity is a kind of bipolar waveform with leader progress considered, which is observed in some experiments. In the calculation, Heidler model was adopted as the lightning current waveform model, the lightning current amplitude was assumed to be 10 kA, $\tau_1 = 1\ \mu\text{s}$, $\tau_2 = 20\ \mu\text{s}$, the height of the observation point is 10 m, and the soil conductivity is 0.005 S/m. The length of the lightning channel is 1950 m. Fig. 2 shows that the leader progress has a significant influence on the waveform of electric field. When the time constant τ_2 of Heidler model reduced to 10 μs, the waveforms of calculated electric field strength would be changed. The distance between the point and the lightning current channel is set as $d = 30$ m. The electric field strength waveform considering the influence of leader is a bipolar waveform, which has also been observed in some experiments.

2.2. The electromagnetic field propagation model

The electromagnetic propagation model is shown in Fig. 3 when the ground is ideal [9–11]. The vertical electric field E_z, the horizontal electric field E_r' and the horizontal magnetic field H_r' are calculated relatively in the following functions:

$$\begin{aligned} E_z(r,z,t) = \frac{1}{4\pi\varepsilon_0}\Bigg(&\int_{-H}^{H}\frac{2(z-z_0)^2-r^2}{R^5}\int_0^t i\left(z_0,\tau-\frac{R}{c}\right)\mathrm{d}\tau\mathrm{d}z_0 \\ &+\int_{-H}^{H}\frac{2(z-z_0)^2-r^2}{cR^4}i\left(z_0,t-\frac{R}{c}\right)\mathrm{d}z_0 \\ &-\int_{-H}^{H}\frac{r^2}{c^2R^2}\frac{\partial i(z_0,t-R/c)}{\partial t}\mathrm{d}z_0\Bigg) \end{aligned} \tag{7}$$