CALCULATION AND ANALYSIS OF LIGHTNING TRIP RATE BASED ON NUMERICAL CALCULATION OF INDUCED OVERVOLTAGE

Rongbin XIE [1*], Jun ZHU[1], Jiangtao LI[2], Yifeng WANG[2]

To assess the risk of the distribution lines caused by lightning, the lightning trip rate of distribution lines should be calculated first. At present, the lightning trip rate caused by the induced voltage of the distribution line is not well considered due to the complexity of correct calculation of induced voltage. In order to better evaluate the influence of the induced overvoltage to distribution lines, numerical calculation of induced voltage should be taken into consideration. The induced voltage is calculated by finite difference time domain (FDTD). The lightning strike trip rate based on numerical calculation is more accurate than the formula calculation. Besides the inductive lightning trip rate, the lightning trip rate calculation of lightning strike line and tower in the range of lightning line distribution range is considered. The actual engineer data verifies the accuracy of the calculation method. At the meantime, it is discussed that some factors that influence the lightning trip rate. It can be seen that different factors have a different influence on the lightning trip rate and the direct lightning trip rate.

Keywords: numerical calculation; induced voltage; lightning trip rate

1. Introduction

Overhead distribution lines are important parts of the power system. With the development of related concepts such as intelligent distribution network, ubiquitous power Internet and other related concepts, the security and stability requirements of distribution line are required more. In fact, for the overhead distribution lines below 110 kV, power failure occurs sometimes due to its lower insulation. The power supply interruption accidents of distribution lines are mostly caused by lightning which causes the insulators to flash [1-3]. There are two main ways for lightning to cause flashover: one is that lightning strikes distribution lines or towers directly, the other is that lightning strikes near the lines which causes induced overvoltage on the lines. Most of the induced overvoltage on the distribution lines is less than 300 kV, which exceeds the insulation level of the distribution line below 110 kV, meaning a threat to the distribution line [4-6]. To ensure the safe and stable operation of the distribution lines, it is necessary to

[1] Guizhou Power Grid, Guiyang Xifeng Power Supply Bureau, Guizhou Guiyang, China
[2] Department of Electrical Engineering, Xi'an Jiaotong University, Xi'an, Shanxi, China
* Corresponding author: 1925915166@qq.com

evaluate the impact of lightning on the distribution line better, based on which, the protection of the distribution line can be strengthened correctly. Therefore, it is important to accurately calculate the risk caused by the lightning to the distribution line. The most basic method for measuring the lightning strike risk of a line is to calculate the lightning trip rate of the line. For the distribution line, the lightning trips caused by the induced lightning cannot be negligible, so it is not as simple as transmission lines which just consider the lightning strike trips caused by striking electric lines or towers.

There have been many studies on calculating the lightning strike trip rate of distribution lines under lightning directly striking electric lines or towers. However, as for the calculation for the induced lightning strike trip rate of the distribution line, the current calculation method is rough because calculation formula of induced overvoltage is often used to obtain the magnitude of the induced overvoltage on the line generated by lightning current [7]. After that, the induced lightning trip rate of the line is calculated with the result [8]. In fact, this calculation is not accurate enough because the formula calculation of the induced overvoltage ignores the influence of factors such as soil resistivity and lightning current return speed on the induced overvoltage on the line [9]. In order to calculate the lightning trip rate caused by the induced overvoltage of the distribution line better, it is essential to have a more accurate calculation of the induced overvoltage. Therefore, the method based on numerical calculation is used to calculate the induced overvoltage of the lines so as to calculate the induced lightning trip rate of the lines, and at the same time the direct lightning strike trip rate of the lines is calculated. Finally, the total lightning strike trip-out rate of the line is obtained, and the lightning risk of distribution lines is evaluated more accurately.

2. Calculation of Induced Voltage

The calculation of the induced voltage of the overhead distribution lines is divided into two steps: Firstly, the electromagnetic field around the lightning path is calculated by the mathematical model of the lightning strikeback. Then, the mathematical model of coupling electromagnetic field around lightning channels with overhead lines is established to calculate the induced lightning overvoltage of overhead distribution lines.

As shown Fig.1, the current of the lightning channel has been divided into infinite current elements. The current elements $i(z',t)dz$ at any height z' can be regarded as the rate of change of an electric dipole with time. The electromagnetic field around the lightning channel can be calculated by calculating the electromagnetic field of each current element and integrating along the whole return channel.

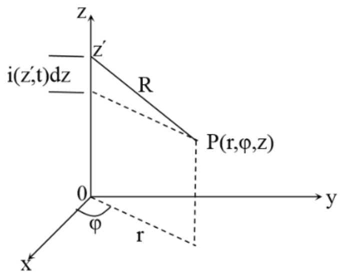

Fig. 1 Calculation of electromagnetic field

Calculation of the electromagnetic field is shown in [10]. After it, induced overvoltage on the line is calculated by the Agrawal model [11]. During the process, induced overvoltage is calculated by numerical calculation based on finite difference time domain (FDTD) method [12,13]. As an example of the induced overvoltage is solved by numerical calculation method: the amplitude of lightning current is 60 kA, the time to crest of lightning current is 2 μs, the time to half value current is 50 μs, the speed of return stroke current is 1.5×10^{8} m/s, the line height is 10m, the horizontal distance between lightning strike point and the distribution line is 100m, the earth conductivity is 0.001 S/m, the soil dielectric constant is 10, and the line length is 500m. The lightning strike point is located at one end of the overhead line. The induced overvoltage of the line nearest to the lightning strike point is calculated as shown in Fig. 2.

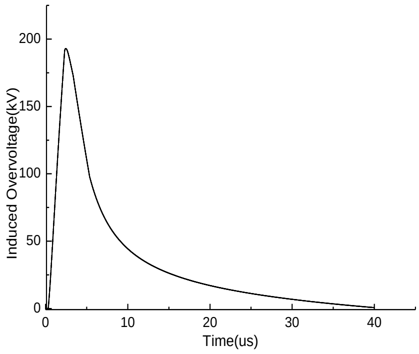

Fig. 2 Induced overvoltage waveform

The maximum value of the induced overvoltage is 193 kV, which is different from the result of formula calculation. The induced tripping rate of the line will be calculated according to the numerical calculation of the lightning induced overvoltage of the line.

3. Calculation of Lightning Strike Trip Rate

The calculation of lightning tripping rate of distribution lines is divided into two parts: one is the line tripping caused by direct lightning strikes on distribution lines or towers; the other is the line tripping caused by induced overvoltage caused by nearby lightning strikes. The calculation of the two parts of the tripping rate will be explained. Before calculating the lightning tripping rate, the relevant lightning parameters need to be clarified first.

3.1 Lightning parameters

For the detailed description of lightning activities, ground lightning density N_g is used, which is the ground flash density in flashes per km^2 per year. This parameter can be calculated by the lightning location system for a specific area. In this paper, the calculation formula recommended by IEEE is used:

$$N_g = 0.04 T_d^{1.25} \tag{1}$$

T_d is annual thunder and lightning day, referring to a thunder and lightning day that can be heard more than once a year.

Besides N_g, the lightning current amplitude is also an important parameter reflecting the characteristics of lightning activity, which is a very important basis for lightning calculation and protection analysis. The GIGRE Working Group considers that the probability of calculating lightning current peaks exceeding I_m is:

$$P = \frac{1}{1 + (I_m / a)^b} \tag{2}$$

The values of a and b can also be simulated and calculated by the measured values of lightning location system, and the probability formula adapting to a specific area can be obtained. In this paper, the recommended values of IEEE - a = 31, b = 2.6 are used.

As shown in section 3.3, the time to crest of lightning current is 2 μs, the time to half value current is 50 μs and the speed of return stroke current is 1.5×10^8 m/s.

3.2 Lightning trip rate when lightning striking on lines or towers

Lightning directly strikes on lines and towers are considered in calculating overhead distribution lines. According to the electrical geometry model, when lightning strikes are located in the range of direct lightning strikes, the probability of lightning strikes on towers is expressed by struck probability g, then the probability of direct strikes on lines is 1-g, and g = 0.5 is generally selected.

When calculating the lightning trip rate of direct lightning, it is necessary to calculate the critical lightning current peak value. For lightning direct strikes, the formulas for calculating the critical lightning current peak value are as follows:

$$I_T = \frac{U_{50\%}}{(R_{ch} + L_t / 2.6 + h_d / 2.6)} \tag{3}$$

$$I_L = \frac{2U_{50\%}}{Z_c} \tag{4}$$

R_{ch} -- tower grounding resistance, Ω;

L_t -- tower equivalent inductance, μH;

h_d -- height of line, m;

$U_{50\%}$ -- 50% disruptive discharge voltage at standard lightning surge (1.2 / 50 μs), kV;

I_t -- peak current during lightning stroke, kA;

I_L -- critical current during lightning stroke, kA [14];

Zc -- the characteristic (surge) impedance of conductor, Ω;

In engineering calculation, considering the probability of lightning current, the probability of lightning current amplitude of 300 kA is very low, so the calculation of the tripping rate TR_T and the tripping rate TR_L of direct lightning is as follows:

$$TR_T = (0.2N_g \int_{I_T}^{300} P(I)y_{min}dI) \cdot \eta \cdot g \tag{5}$$

$$TR_L = (0.2N_g \int_{I_L}^{300} P(I)y_{min}dI) \cdot \eta \cdot (1-g) \tag{6}$$

η -- is rate;

y_{min} -- critical distance of lightning striking lines, m;

$P(I)$ -- cumulative probability of lightning current peak greater than I.

For the effective grounding of isolated neutral system in distribution network, the arc rate is solved as follows:

$$\eta = 0.01 \cdot [4.5 \cdot (\frac{U_e}{2l_j + l_m})^{0.75} - 14] \tag{7}$$

U_e -- rated line voltage, kV

l_j -- the length of insulator string, m

l_m -- the distance from the base of insulator to tower (l_m =0 for iron and reinforced concrete lines), m

$$y_{min} = \sqrt{r_s^2 - (r_g - h_d)^2} \tag{8}$$

r_s is the lightning strike distance of the wire, and r_g is the lightning strike distance of the earth.

$$r_s = 10I^{0.65} \tag{9}$$

$$r_g = [0.36 + 0.17ln(43 - h_d)] \cdot r_s \tag{10}$$

3.3 Lightning trip rate of induced voltage

The numerical calculation method of induced overvoltage is used. As shown in section 2, the induced voltage on the lines is calculated and the maximum value U_{max} is taken. U_{max} is a function of the lightning current I and the distance S which is between the lightning strike point and the line. That is, $U = f(I,S)$. When $U_{max}>U_{50\%}$, the insulator flashes, so according to the $U_{50\%}$ of the insulator, the critical flashover distance y_{max} when the peak value of the lightning current is I can be obtained. Insulation flashover occurs when the distance between the line and the lightning strike point is less than y_{max}.

The tripping rate TR_I of line induced lightning stroke is calculated as follows:

$$TR_I = (0.2N_g \int_{I_L}^{300} P(I)(y_{max} - y_{min})dI) \cdot \eta \tag{11}$$

The total trip rate of distribution lines is:

$$TR = TR_T + TR_L + TR_I \tag{12}$$

4. Calculation Results and Analysis of Lightning Strike Rate

4.1 Calculation of lightning trip rate of distribution lines

One 10 kV distribution line in a certain place is taken as the research object: pole tower as cement pole, conductor average height is 12 m, grounding resistance is 10 Ω, insulator 50% discharge voltage $U_{50\%}$ = 118 kV, the creepage distance is 280 mm (the minimum creepage distance being 25 kV/mm for the considered pollution area), annual average Thunderstorm Day in the area where the line is located is 70 D, earth conductivity = 0.001 S/m. According to the above calculation method, the direct lightning trip-out rate of this line is 16.1 times/(100 km·a), the induction lightning trip-out rate is 43.2 times/(100km·a), and the total lightning trip-out rate is 59.3 times/(100km·a).

According to statistics, the average number of trips occurred in the past three years due to lightning strikes is 5. The total length of the line is about 8.8 km, which is converted into an average lightning trip-out rate of 56.8 times/(100km·a). Compared with the actual situation, the annual average lightning trip-out rate error of theoretical calculation is 4.4%, which meets the requirements of engineering prediction.

4.2 Influence of different factors on lightning trip rate of lines

4.2.1 Lightning parameters

Considering the influence of average Thunderstorm Day on line trip rate, the insulator with $U_{50\%}$ = 118 kV and 280 mm insulation distance is adopted. Other line parameters and environmental parameters remain unchanged, the same with parameters in section 4.1. The average Thunderstorm Day is 40, 50, 60 and 70 days respectively. The lightning trip rate of line is calculated as shown in Table 1.

Table 1

Comparison of lightning tripping rates of transmission lines on different thunderstorm days

Times/(100km·a)

Average Thunderstorm Days/d	TR_T+TR_L	TR_I	TR
40	7.8	20.9	28.7
50	10.4	27.9	38.3
60	13.1	35.3	48.4
70	16.1	43.2	59.3

From Table 1, it can be seen that with the increase of average thunderstorm days, the lightning trip rate of distribution lines increases. The average thunderstorm days have an impact on both direct lightning trip rates and inductive lightning trip rates of lines, which means that it should be paid more attention to those towers that are located in higher ground lightning density N_g.

4.2.2 Insulator parameters

Low insulation level is the important factor of frequent lightning tripping accidents in distribution lines. Strengthening insulation can improve lightning resistance of lines. The lightning tripping rates of lines with different insulator parameters are analyzed. The direct lightning trip rate and induction lightning trip rate under different insulation configurations are calculated respectively, while the circuit parameters and environmental parameters remain unchanged. The results are shown in Table 2.

Table 2

Comparison of lightning tripping rates of transmission lines with different insulator parameter

Times/(100km·a)

Insulator Number	$U_{50\%}$/kV	Insulation Distance/mm	TR_T+TR_L	TR_I	TR
A	118	280	16.1	43.2	59.3
B	140	370	11.3	23.8	35.1
C	165	400	10.1	16.4	26.5
D	118	480	7.7	20.8	28.5
E	185	320	13.6	18.0	31.6
F	210	380	10.7	11.3	22.0
G	100	320	13.7	46.0	59.7

From Table 2 line 5 and line 7, it can be seen that under the same insulation distance, the discharge voltage $U_{50\%}$ of insulators has little effect on the lightning trip rate of direct lightning strikes, but it affects the inductive lightning trip rate of lines much more, so higher $U_{50\%}$ of insulators is necessary to reduce the lightning trip rate. From Table 2 line 1 and line 4, under the same $U_{50\%}$, the longer the insulation distance, the lower the total lightning trip rate. In general, $U_{50\%}$ has an effect on the inductive lightning trip rate, the insulation distance has an effect on both the inductive lightning trip rate and the direct lightning trip rate.

4.2.3 Soil resistivity

Considering the influence of soil resistivity on line trip rate, the insulator with U50% = 118 kV and 280 mm insulation distance is adopted. Other parameters remain unchanged. Soil resistivity is 100, 500 and 1000 Ω·m respectively. The lightning trip rate of line is calculated as shown in Table 3.

Table 3

Comparison of lightning tripping rates of transmission lines under different soil resistivity

Times/(100km·a)

Soil resistivity/Ω·m	TR_T+TR_L	TR_I	*TR*
1000	16.1	43.2	59.3
500	16.1	38.1	54.2
100	16.1	31.4	47.5

As can be seen from Table 3, with the increase of soil resistivity, the total lightning trip rate increases. The most influential factor is the line induced lightning trip rate. The reason is that soil resistivity has a great influence on the value of induced overvoltage on the line, thus affecting the line induced lightning trip rate.

4.2.4 Height of lines

Considering the influence of line height on line tripping rate, the insulator with $U_{50\%}$ = 118 kV and 280 mm insulation distance is adopted. Other line parameters and environmental parameters remain unchanged. Height of lines is 12, 14 and 16 m, respectively. Lightning tripping rate of line is calculated as shown in Table 4.

Table 4

Comparison of lightning tripping rates of transmission lines with different height of lines

Times/(100km·a)

Height of lines/m	TR_T+TR_L	TR_I	*TR*
12	16.1	43.2	59.3
14	17.3	49.1	66.4
16	18.4	55.0	73.4

Table 4 shows that with the increase of the average height of distribution lines, the direct lightning trip rate and the induction lightning trip rate of the lines both increase. The reason is that the higher the lines, the more chances which they will be stroke by lightning. And at the same time, when the lines are higher, the induced voltage on the lines is higher, so it influences the induction lightning trip rate.

5. Conclusion

This paper presented a study on lightning trip rate of distribution lines. Firstly, the lightning trip rate of induced voltage is calculated by numerical calculation, which is closer to a actual voltage. Of course, the lightning trip rate of direct lightning is calculated in the paper.

Based on that, four kinds of factors influencing the lightning trip rate has been discussed:

(1) The average thunderstorm days have an impact on both direct lightning trip rates and inductive lightning trip rates of lines, so it reminds that we should pay more attention to those zones with higher ground lightning density N_g.

(2) As for the influence of insulators, under the same insulation distance, the discharge voltage $U_{50\%}$ of insulators has little effect on the lightning trip rate of direct lightning strikes, but it affects the inductive lightning trip rate of lines much more. Under the same $U_{50\%}$, the longer the insulation distance, the lower the direct lightning trip rate and the inductive lightning trip rate.

(3) Soil resistivity has no effect on direct lightning trip rate, it only influences the inductive lightning trip rate. With the increase of soil resistivity, the total lightning trip rate increases.

(4) With the increase of the average height of distribution lines, the direct lightning trip rate and the induction lightning trip rate of the lines both increase.

Compared with the European technical method, this paper calculates the lightning trip rate of induced voltage by numerical calculation, which is closer to the actual voltage. It solves the problem that the current calculation method is relatively rough because the calculation formula of induced overvoltage is often used to calculate the induced overvoltage of lightning current on the line. As the calculation formula of induced over-voltage ignores the influence of soil resistivity, return speed of lightning current and other factors on the induced over-voltage of the line, the calculation is not accurate enough. The accuracy of the calculation method is verified by the actual engineering data.

R E F E R E N C E S

[1]. *H. Taniguchi, H. Sugimoto, S. Yokoyama*, "Observation of lightning effect on power distribution lines by still cameras", in Electrical Engineering in Japan, **vol. 119**, no. 1, pp. 17-23, 2015.

[2]. *M. Izadi, M. S. Abd Rahman, M. Z. Abkadir, et al.*, "The influence of lightning induced voltage on the distribution power line polymer insulators", in Plos One, **vol. 12**, no. 2, e0172118, 2017.

[3]. *H. Taniguchi, H. Sugimoto, S. Yokoyama,* "Study Concerning Production of Lightning Overvoltages on Low-Voltage Power Distribution Lines", in Electrical Engineering in Japan, **vol. 130**, no. 4, pp. 66-75, 2015.

[4]. *J. O. S. Paulino, C. F. Barbosa, I. J. S. Lopes, et al.*, "Assessment and analysis of indirect lightning performance of overhead lines", in Electric Power Systems Research, **vol. 118**, no. 4, pp. 55-61, 2015.

[5]. *J. Chen, M. Zhu*, "Calculation of Lightning Flashover Rates of Overhead Distribution Lines Considering Direct and Indirect Strokes", in IEEE Transactions on Electromagnetic Compatibility, **vol. 56**, no. 3, pp. 668-674, 2014.

[6]. *Y. Z. Yu, J. K. Ni, J. Y. Han, et al.*, "Influence of Overhead Ground Wire Height and Impulse Ground Resistance on Lightning Protection Performance of Distribution Line", in Advanced Materials Research, **vol. 1092-1093**, pp. 281-287, 2015.
[7]. *J. Chen, M. Zhu, H. Wang, et al.*, "Calculation model of lightning induced overvoltage using PSCAD /EMTDC program for overhead distribution lines", in Journal of China University of Petroleum, **vol. 38**, no. 4, pp. 192-199, 2014.
[8]. *Z. Yu, Z. Tong, Z. Wang, et al.*, "Calculation and experiment of induced lightning overvoltage on power distribution line", in Electric Power Systems Research, **vol. 139**, pp. 52-59, 2016.
[9]. *S. Sekioka*, "Equivalent Circuit of Distribution Line for Lightning - Induced Voltage Analysis Using Analytical Formulas", in Electrical Engineering in Japan, **vol. 199**, no. 3, pp. 610-616, 2017.
[10]. *M. J. Master, M. A. Uman*, "Transient electric and magnetic fields associated with establishing a finite electrostatic dipole", in American Journal of Physics, **vol. 51**, no. 2, pp. 118-126, 1983.
[11]. *A. K. Agrawal, H. J. Price, S. H. Gurbaxani,* "Transient response of multiconductor transmissions lines excited by a monuniform electromagnetic field", in IEEE Transactions on Electromagnetic Compatibility, **vol. 22**, no. 2, pp. 119-129, 1980.
[12]. *A. Tatematsu, T. Noda,* "Three-Dimensional FDTD Calculation of Lightning-Induced Voltages on a Multiphase Distribution Line with the Lightning Arresters and an Overhead Shielding Wire", in IEEE Transactions on Electromagnetic Compatibility, **vol. 56**, no. 1, pp. 159-167, 2014.
[13]. *J. O. S. Paulino, C. F. Barbosa, I. J. S. Lopes*, "An efficient time - domain method for lightning induced voltage calculation on a finite - length horizontal overhead conductor above lossy ground", in International Transactions on Electrical Energy Systems, **vol. 24**, no. 10, pp. 1493-1504, 2015.
[14]. *T. H. Thang, Y. Baba, V. A. Rakov, et al.,* "FDTD Computation of Lightning-Induced Voltages on Multiconductor Lines with Surge Arresters and Pole Transformers", in IEEE Transactions on Electromagnetic Compatibility, **vol. 57**, no. 3, pp. 442-447, 2015.