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Study on the calculation of shielding failure for dc transmission lines

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Abstract: Lightning is the main cause of transmission line failure, and it is important to improve the lightning protection level of the transmission line for the stability of the power system. Traditional solutions for the shielding failure of transmission lines is to use the electrical geometric model method. However, with the improvement of the voltage level, the physical size increases, and the calculation of lightning protection for ultrahigh-voltage dc lines has a greater difference with operating experience. Based on the Ningxia-Shandong dc transmission lines in China, this study utilised the lead development model to describe the flashover of insulators and the breakdown of the gaps. A comprehensive calculation method of shielding failure trip-out rate considering terrain, earth resistance and weather was proposed. The accuracy was much higher when compared with the traditional calculation and the result can be a reference for other similar calculation for dc lines.

1 Introduction

The safety and stability of the extra-high voltage (EHV) or ultrahigh-voltage dc transmission lines are significant to the power systems. With the development of the power systems and higher voltage level, the accidents caused by lightning are increasing and thus causing great economic loss to the whole society. As recorded, the accidents caused by lightning accounts for 40−70% of all accidents [1–3]. The dc transmission lines play an important role in connecting various power systems and transmitting energy for a long distance, so the lightning protection of dc transmission lines is one of the key subjects for the stability of power systems [4, 5].

Lightning protection performances of transmission lines for various voltage levels have been widely studied throughout the world [6–8]. The accidents caused by lightning include shielding failure and counterattack failure. The former means that the lightning hits the transmission lines across ground wires, and the latter means that the lightning hits the tower and then causes the insulators flashover. The traditional solution of shielding failure is to use the electro-geometric model, which means modelling the structure of transmission lines into the electrical geometric model [9, 10]. The original model was obtained according to the operating experience of 110 kV transmission lines on the plains, but present towers are higher, so the calculation error using this model can be unacceptable.

Based on the ±660 kV dc transmission lines from Ningxia to Shandong, the manuscript models the transmission lines into leader development models and carries out corresponding electromagnetic transient calculation. Lightning protection performances of transmission lines were studied, expecting to offer a reference for the design and construction of the EHV dc transmission lines.

2 Methodology

2.1 Research on lightning parameters

The lightning parameters are the key parameters to show the regularity of lightning activities, thus are significant to the lightning protection of transmission lines. Thunderstorm days, lightning density, and amplitude cumulative probability of lightning current are chosen. The following results are based on the observation results of lightning location systems in China from 2007 to 2014.

According to the IEEE standard, the relationship between thunderstorm days and lightning density is as follows:

$$N_g = \alpha T_d^{\gamma} \quad (1)$$

where N_g represents the lightning density and T_d stands for the thunderstorm days. As for α and γ, it is recommended that α is 0.04 and γ is 1.25 in the IEEE standard. However, in the electrical industry standard of China, the results are 0.023 and 1.3 [11]. The differences can be much larger when T_d is bigger. To obtain the accurate relationship between N_g and T_d, the manuscript made a nonlinear fitting and the results were shown in (2) and Fig. 1.

$$N_g = 0.0509 T_d^{0.8425} \quad (2)$$

As shown in Fig. 1, when T_d is small, the relationship curses using recommended parameters of two standards are close to the observation and the fitting curses. However, as T_d increases, the differences between the theoretical values and the real ones begin to be larger. The calculation error can be unacceptable when using estimated parameters, so it is necessary to determine proper parameters according to the observation results.

Besides, the polarity of the lightning current is one of the key parts of lightning parameters [12–14]. According to the results recorded from 2007 to 2014, the negative lightning accounts for 97.84% of the whole lightning occurred in China, which is consistent with the other observation results. The proportion of the positive lightning current is lower, but the amplitude is usually higher. The amplitude cumulative probability of the lightning current along the transmission line is analysed, as shown in Fig. 2. This result will be used for the calculation of the lightning tripping rate in the following section.

2.2 Leader development model of insulators

The direct cause of lightning tripping out is that the lightning hits the tower or the transmission lines, and then the voltage over the insulators increases and causes flashover across the insulators. One of the criteria to judge whether the flashover has occurred is comparing the peak voltage and the $U_{50\%}$ of the insulators. When

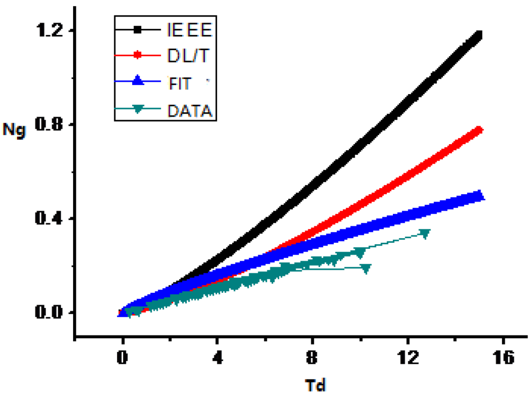

Fig. 1 *Relationship between N_g and T_d*

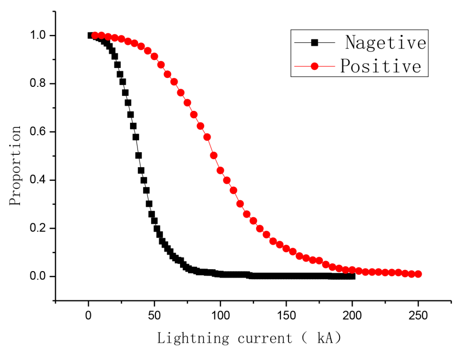

Fig. 2 *Amplitude cumulative probability of the lightning current*

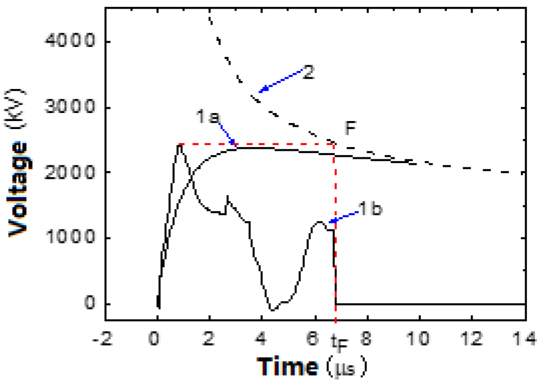

Fig. 3 *Criterion to judge whether the flashover occur*

the peak voltage across the insulator is higher than its $U_{50\%}$, the flashover is considered to occur and the moment can be estimated according to the discharge delay [15–17].

The above criterion can be described as Fig. 3. The *U–t* characteristic curve of the insulator when suffering standard impulses is traditionally used to judge whether the flashover occur. As shown in Fig. 3, the curse 1a stands for the standard lightning voltage across the insulator. The curse 2 stands for the *U–t* characteristic curve of the insulator when suffering standard impulses. A parallel extension cord through the peak of curse 1a meets the curse 2 with pot *F*, and the moment t_F is estimated as when flashover occurs.

At the same time, the curse 1b stands for the measured voltage across the insulator when suffering lightning impulse current. So according to the criterion, the *tF* is the same in these two situations when the waveforms are utterly different. This means that the flashover occurred is determined by just the peak voltage across the insulator but not by the waveform, which is absolutely contrary to the experiment results. The calculation error will be relatively larger when using this criterion.

Precious studies have shown that when suffering the impulse voltage, the discharging for the long gap includes several processes [18, 19], which can be described as follows:

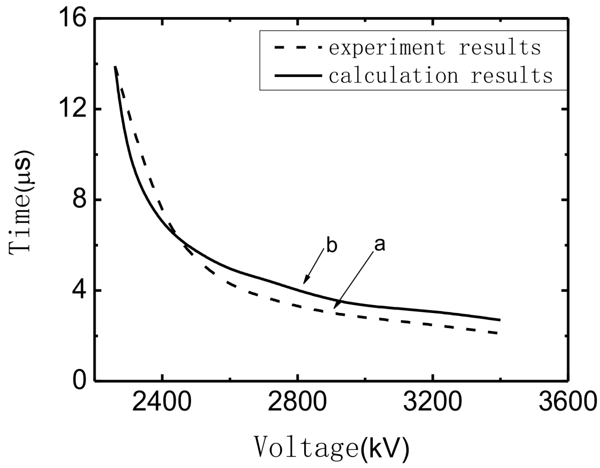

Fig. 4 *U-t characteristic curses of calculation and experiments*

$$T_B = t_p + T_S + T_i + T_L + T_g \quad (3)$$

where T_B stands for the time it takes to finish the whole discharge, t_p and T_s stand for the time corona takes to born and develop, T_i and T_L stand for the time it takes for the leader and the ionisation wave to develop. T_g stands for the time it takes for the air to heat up. Among these, T_i, t_p, and T_g are usually negligible, so the formula can also be simplified as follows:

$$T_B = T_S + T_L \quad (4)$$

T_s can be calculated as follows:

$$T_s = \frac{1}{k_1(E/E_{50}) - k_2} \quad (5)$$

Among them, E_{50} stands for the average value of the electric field with $U_{50\%}$ and E stands for the maximum of the electric field before the flashover. k_1 can be estimated to be 1.25 and k_2 to be 0.95. The development speed of the leader can be calculated as follows:

$$V_l = k_3 d\, e^{k_4(U/d)} \cdot \left(\frac{U(t)}{x} - E_0\right) \quad (6)$$

where E_0 is a constant determined by gap characteristics and can be estimated as 500 kV/m, *d* is the distance of the gap and *U* stands for the voltage across it, *x* stands for the distance when the discharge has not occurred, and *k*3 and *k*4 can be estimated to be 170 and 1.5×10^{-3} according to the precious experience [20].

Using the above formulas, the *U–t* characteristics of insulators can be described as shown in Fig. 4.

Since the leader development method is based on the experiments, the equivalent gap distance must be accurate when using this. For ordinary insulators, the flashover path is shown in Fig. 5.

L stands for the length of the flashover path, *h* and *D* stand for the height and width of each insulator, respectively, *n* stands for the number of insulators. So the length of the gap distance can be described as follows:

$$L = (n - 1) \times h + D \quad (7)$$

2.3 Leader development model of lightning currents

Considering the effect of ground capacity, the closer the leader is to the ground, the larger its charge density. Precious observation has shown that the charge density in the head of the leader is much higher than the other part [21]. So the charge distribution can be estimated to be exponential.

The amount of charges in the leader is considered to be related to the amplitude of the lightning current. At the same time, the

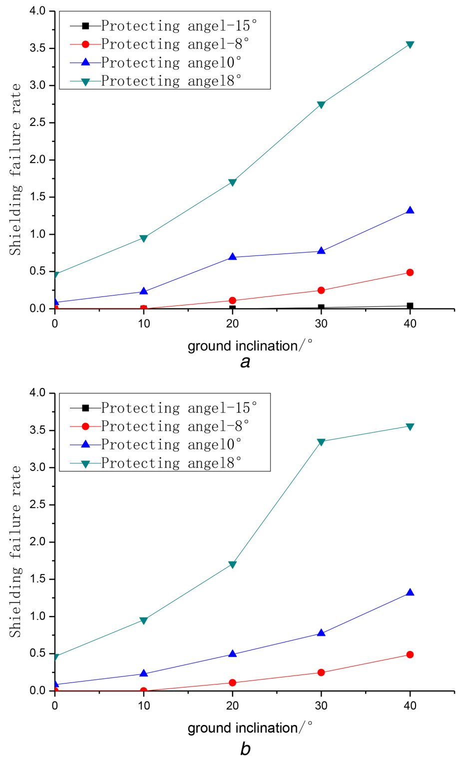

Fig. 6 *Comparison of shielding failure rate in different situations*
(a) Shielding failure rate on the hill, ***(b)*** Shielding failure rate in a valley

head of the leader is usually half-spherical and the radius of which is related to the amount of charge in the leader. So the radius R can be described as formula follows:

$$R = 3\lg(I + 20) \tag{8}$$

Many bifurcations may occur along the lightning path when the leader develops to the ground. However, on the whole, the leader can be considered to develop towards where the electric field intensity is higher. In this manuscript, the branches of lightning path are ignored and the leader is considered to develop towards where the electric field intensity is higher. When it comes to the calculation of shielding failure, the above assumption is definitely correct.

As for the criterion of the beginning of the leader, the average electrical field intensity is the strictest one. The speed of the negative upward leader can be estimated to be 5–10 cm/μs and the positive one be 0.25–1 times of it.

2.4 Calculation of the shielding failure rate

Based on the above leader development method, the lightning position, whether the ground wire of transmission lines, can be obtained. To calculate the shielding failure rate, this manuscript divided the lands into squares, the area of which was Si (m^2). Then the scale of the lightning currents, I_{1i} and I_{2i}, were calculated when the leader located in each square and the shielding failure occurred. The shielding failure occurred in each square can be described as follows:

$$N_i = 10^{-6} T_d S_i \gamma \int_{I_{2i}}^{I_{1i}} p(I)\,\mathrm{d}I \tag{9}$$

where $p(I)$ stands for the amplitude cumulative probability of the lightning current, as shown in Fig. 2. γ stands for the lightning intensity. So the shielding failure rate along the transmission line is the sum of Ni, as shown below

$$a = \sum_i N_i \tag{10}$$

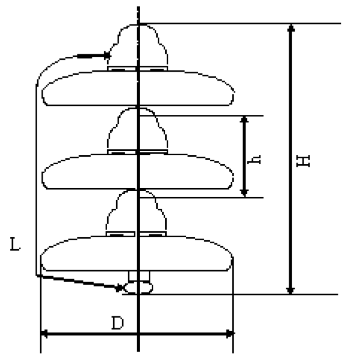

Fig. 5 *Flashover path of the insulators*

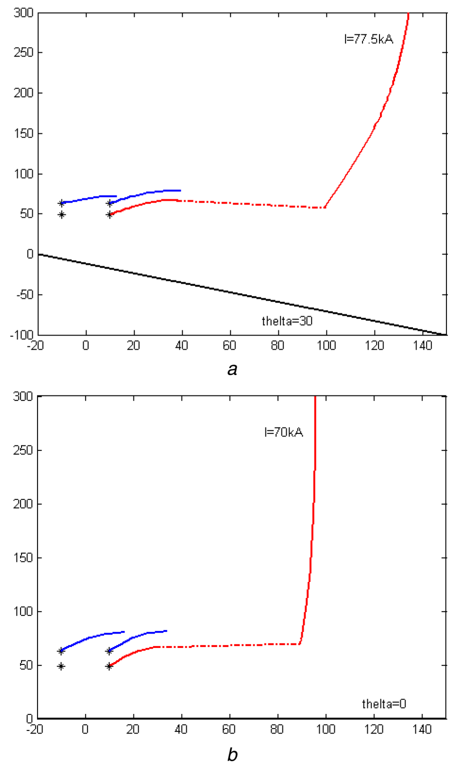

Fig. 7 *Comparison of leader development in different situations*
(a) Leader development when the lines are on the hill, ***(b)*** Leader development when the lines are on the plain

3 Results

The leader development models of insulators and lightning currents were established as above and based on which, the shielding failure rate of the dc transmission line can be calculated. Taking the ±660 kV dc transmission lines from Ningxia to Shandong in China as an example, the manuscript calculated the shielding failure rate of the whole line and compared the results with the operating experiences.

3.1 Shielding failure rate with different situations

In this manuscript, the thunderstorm day is estimated to be 80 day per year and the amplitude cumulative probability of the lightning current is shown in Fig. 2. Due to the various polarities of two operating lines, the shielding failure rates in different situations are utterly different. Most lightning current in nature is negative and thus the positive line will be hit more than the negative one. So in the calculation, the worst situations are discussed. For example, the positive line is higher to the ground than the negative one when placed in a valley.

The calculation results are shown in Figs. 6 and 7.

As shown in Fig. 6, the shielding failure rates on the hill or in the valley are compared. It shows that when the ground inclination

Table 1 Shielding failure rate of the whole line

Line label	Shielding failure rate calculated	Shielding failure rate of operating lines
1	5.08	5.35
2	2.07	2.30
3	1.01	1.02
4	4.61	4.87

increases, the shielding failure rate becomes larger. So it is with the protecting angel. This is consistent with the operating experience.

Fig. 7 shows the shielding effect with various terrains. When the protecting angle is 0° on the hill, the protection characteristic of the ground wire is relatively poor. The downward leader develops towards the transmission line obviously.

3.2 Shielding failure rate of the whole line

To sum up, the terrains along the transmission line are divided into plain, hill, and valley. The proportions of them are calculated according to the topographic map. Different terrains are distinguished by the ground inclination angel. On this assumption, the calculation result of the whole transmission line is shown as Table 1.

As shown in Table 1, the calculation result using the leader development method is consistent to the operating experience.

4 Conclusion

Based on the ±660 kV dc transmission lines from Ningxia to Shandong, the manuscript models the transmission lines into leader development models and carry out corresponding electromagnetic transient calculation. The lightning protection performances of transmission lines were studied. The calculation result shows that the leader development method is consistent with the operating experience.

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6 References

[1] Xiaogang, G.: 'DC transmission line protection feature research'. PhD thesis, Changsha University, 2012

[2] Zhenya, L.: '*High voltage dc transmission theory*' (China Power Press, Beijing, 2009)

[3] Wing-Jun, W.: 'Current situation and analysis of lightning damage in DC transmission lines'. *High Volt. Electr. Appl.*, 2014, **50**, (5), pp. 134–137

[4] Wuhan High Pressure Institute: 'Several problems in the design of lightning tripping rate and 500 kV ultra high voltage circuit'. 1982

[5] Verrikin, W.: 'The experience in lightning protection of ultra-high voltage and ultra-high voltage transmission lines in Russia', *High Volt. Technol.*, 1998, (2), pp. 76–79

[6] Hu, Y.: '*Fault analysis and prevention of transmission lines*' (China Power Press, Beijing, 2007)

[7] China Electric Power Research Institute: '*The state grid corporation +500 kV inter-district HVDC project external insulation fault analysis (2004 ~ 2007)*' (China Electric Power Research Institute, Beijing, 2008)

[8] Shelemy, S.J., Swatek, D.R.: 'Monte Carlo'simulation of lightning strikes to the Nelson river HVDC transmission lines'. Int. Conf. on Power Systems Transients, Rio de Janeiro, Brazil, 24–28 June 2001, pp. 247–257

[9] Zhang, W.-M., Gao, Y.-M.: '*Overvoltage protection and insulation*' (Tsinghua University Press, Beijing, 1987), pp. 193–195

[10] Zakaria, Z., Bashi, S.M., Mailah, N.F.*, et al.*: 'Simulation of lightning surges on tower transmission using PSCAD/EMTDC: a comparative study'. IEEE Student Conf. on Research and Development (SCORe D 2002), Shah Alam, Malaysia, 16–17 July 2002, pp. 426–429

[11] Ministry of Power Industry, China: '*DL/T620-1997 ac electrical devices over voltage protection and insulation coordination*' (China Power Press, Beijing, 1997)

[12] Rizk, F.A.M.: 'Switching impulse strength of air insulation: leader inception criterion', *IEEE Trans. Power Deliv.*, 1989, **PWRD-4**, (4), pp. 2187–2195

[13] Dellera, L., Garbagnati, E.: 'Lightning strokes simulation by means of the leader progression model part I: description of the model and evaluation of exposure of free-standing structure', *IEEE Trans. Power Deliv.*, 1990, **PWRD-5**, (4), pp. 2009–2022

[14] Young, E.S., Clayton, J.M., Hileman, A.R.: 'Shielding of transmission lines', *IEEE Trans. Power Appar. Syst.*, 1963, **S82**, pp. 132–154

[15] Brown, G.W, Whitehead, E.R.: 'Field and analytical studies of transmission line shielding: part II', *IEEE Trans. Power Appar. Syst.*, 1969, **88**, (5), pp. 617–626

[16] Li, Y.: '*Research on the anti-lightning strategy in the southern electric power grid*' (Tsinghua University Electrical Engineering Department, Beijing, 2007)

[17] Huang, W.: '*Research on thunder performance in high-voltage dc overhead transmission lines*' (Electrical Engineering Report of Tsinghua University, Beijing, 1989)

[18] Zhou, Y., Yang, X., Zhang, Z.*, et al.*: 'Statistical analysis of lightning parameters in Qinghai province'. Qinghai power, 2013, (12), pp. 4–7

[19] IEEE: IEEE Std 1234-1997, IEEE Guide for Improving the Lighting Performance of Transmission Lines'. 1997

[20] Insulation Coordination Standardization Technical Committee of Ministry of Power Industry in China: '*DL/T620-1997 AC electrical devices over voltage protection and insulation coordination*' (China Power Press, Beijing, 1997)

[21] Du, P.: 'Modification of several parameters and methods in the lightning protection calculation of transmission lines', *Power Grid Technol.*, 1996, **20**, (12), pp. 53–56