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The Calculation Method of Shielding Failure Trip Rate of UHV Transmission Lines in Mountainous Areas

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Abstract. Since the second industrial revolution, electric energy has always been the most important and indispensable clean energy in the international community. As a kind of transmission technology with small loss ratio and long transmission distance, UHV transmission is widely used and vigorously promoted in the world. However, UHV transmission lines are often assumed to be vulnerable to thunderstorm discharge in some harsh geographical environment. In order to improve the calculation accuracy of line shielding failure rate, an improved electrical geometric model is proposed to study the shielding failure characteristics of transmission lines under complex mountainous areas, and various typical characteristics including mountain tops, valleys, slopes, climbing, and crossing trenches are summarized.

1 Introduction

The voltage range of Ultra-high voltage (UHV) is from 330kV to 765kV, including 330kV, 400kV, 500kV, 765kV, etc. UHV long-distance transmission is an inevitable requirement with the increase of power generation capacity and power load, and it is also an important symbol of the development level of power system [1]. With the development of power consumption scale, large capacity hydropower stations, thermal power stations and nuclear power stations are built far away from the load centre [2][3]. Using UHV level for long-distance power transmission can produce high economic benefits. UHV transmission can increase the transmission capacity and extend the transmission distance, reduce the transmission cost per unit power, greatly reduce the transmission loss, save the scale of transmission corridor, and have significant economic benefits and social value [4]. Moreover, the dispatching between power systems can also adopt the mode of ultra-high voltage level long-distance power transmission. The advantages of UHV transmission lines are obvious in construction cost, operation cost per kWh and line consumables [5-8].

The growth of power grid transmission capacity and the improvement of transmission line voltage pose a severe challenge to the reliable operation of transmission lines [9]. The research shows that the lightning strike mainly threatens the smooth operation of 500kV UHV transmission lines. In the actual operation process, lightning shielding failure in high-voltage transmission lines causes the increase of lightning trip out rate, especially in mountainous areas, hills and some special areas [10]. The key to improve the reliable operation of power grid is to limit the lightning shielding failure rate. For 500 kV UHV transmission lines, it is important to determine the lightning shielding failure rate and study the economic and rationality of lightning shielding failure prevention measures, so as to reduce the line trip accidents caused by lightning shielding failure, which plays an important role in the reliable operation of transmission lines. Because the occurrence of lightning is a highly random natural process, it is very difficult to simulate and reproduce the formation of lightning under experimental conditions. The mastery of the laws of lightning phenomena makes lightning simulation methods also diverse. Regulation method, distance method, pilot method and fractal method are commonly used methods to describe lightning phenomena. Models based on these methods to simulate the lightning discharge process will also be different. It is difficult to have a unified theoretical method that can comprehensively simulate the overall process of lightning flashover.

There are many factors leading to the tripping of switchgear in the transmission system, and the highest proportion of accident causes is lightning impulse, which is about 50% [11-13]. Long distance transmission lines are usually set up in complex geographical conditions, so the

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possibility of lightning damage is high. Moreover, due to the higher voltage level and the higher tower height, the overall scale of the transmission corridor is outstanding. These conditions increase the lightning radius and make the EHV long-distance transmission line more vulnerable to lightning damage. Therefore, more strict specifications are put forward for lightning protection measures.

2 Application of EGM in mountainous areas

The electrical geometry model is a kind of geometric calculation model which is established by connecting the discharge characteristics of lightning with the structure size of the line. Its basic principle is based on the following concepts and assumptions[14]:

(1) It is uncertain before the lightning leader reaches the critical strike distance of the object to be struck, and the lightning leader will discharge to the object within the strike distance; (2) The strike distance is a function of lightning current, which is related to the amplitude of lightning current.

2.1 Basic principles of electrical geometry model

The electrical geometry model was developed in 1960. At that time, the researchers considered the tower height, shielding angle of lightning line, tower and ground tilt angle and other objective factors to analyse the shielding performance and lightning stroke characteristics of transmission line tower structure. Whitehead proposed an EGM based on "flash distance".

$$r_c = 0.72 I^{0.8} \tag{1}$$

At the same time, E.R. Love's[15] formula based on special circumstances is as follows:

$$r_c = 10 I^{0.65} \tag{2}$$

r_c is the strike distance, m; I is the amplitude of lightning current, kA; It can be obtained by Formula (1), (2) that the lightning current I is positively correlated with the lightning distance r_c, and the area of lightning conductor may decrease. When the lightning current increases to a certain value I_m, the $C'D'$ arc length is zero, which means that the lightning can hit the lightning wire or ground, and there is no lightning shielding failure.

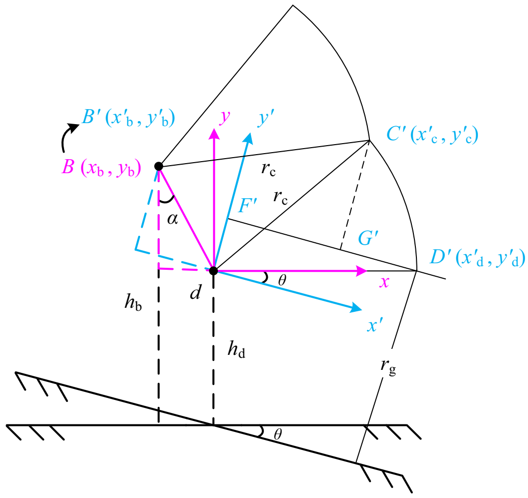

Figure 1. EGM considering ground inclination θ

In order to analyse the shielding failure rate of transmission lines under complex terrain, the ground dip angle should be introduced. The ground inclination is θ. In this case, the EMG is shown in Figure 1. h_b and h_d in the figure are the height of lightning conductor and conductor respectively; If the ground rotates counter clockwise along the horizontal plane θ, Then the ground inclination angle is recorded as -θ; α is the shielding angle of the lightning conductor; r_c is the strike distance of conductor; r_g is the ground strike distance.

The coordinate system of the rectangular coordinate *xdy* is transformed into a new coordinate system *x'dy'*. Here we have the equations (3)-(6):

$$\begin{cases} (x_c' - x_b')^2 + (y_c' - y_b')^2 = r_c^2 \\ x_c'^2 + y_c'^2 = r_c^2 \end{cases} \tag{3}$$

$$\begin{cases} x_d'^2 + y_d'^2 = r_c^2 \\ y_d' = r_g - h_d \cos\theta \end{cases} \tag{4}$$

$$\begin{cases} x_b' = x_b \cos\theta + y_b \sin\theta \\ y_b' = y_b \cos\theta - x_b \sin\theta \end{cases} \tag{5}$$

$$\begin{cases} x_b = \dfrac{(h_b - h_d)\sin(\pi - \alpha)}{\cos\alpha} \\ y_b = h_b - h_d \end{cases} \tag{6}$$

It can be seen from Figure 1, $\overline{G'D'} = x_d' - x_c'$ and $\overline{F'D'} = x_d'$. Therefore, the shielding failure rate p_α under lightning current I can be calculated by formula (7)

$$p_\alpha = \frac{\overline{G'D'}}{\overline{F'D'}} = \frac{x_d' - x_c'}{x_d'} \tag{7}$$

E. R. Whitehead also assumes that the strike distance between the lightning and the ground and the tower is equal. This assumption has less calculation error for the transmission system whose tower is close to the ground. Ignoring the lightning shape and adjacent coupling effect will produce larger calculation error, so it is necessary to further use the strike distance coefficient to modify the 500kV transmission line model. According to the selection basis of strike distance coefficient in 500 kV ultra-high voltage level long-distance transmission line, reference [17] considered the strike distance coefficient and studied the influence of shielding failure trip out rate of ultra-high voltage level long-distance transmission line. When the strike distance coefficient is increased from 0.6 to 1.0, the probability of equipment trip caused by lightning shielding failure of transmission line is significantly reduced, which is about 22.4 times lower. Therefore, the factor of strike distance coefficient should be considered when studying the probability of equipment trip caused by lightning shielding failure of 500 kV ultra-high voltage long-distance transmission line.

2.2 Relationship between ground inclination angle and shielding rate

The terrain where the transmission line is erected generally crosses the hills from the plain, and sometimes crosses the hillside. Statistically, the probability of lightning shielding failure at the top of the hillside is much higher than that in the plain area. However, the variation of terrain cannot be reflected when the code method is used to calculate the shielding rate, so the difference of height cannot reflect the difference of shielding rate. Most of the lightning fault points occur in mountainous areas and hilly areas, outside the hillside, at the top of the ridge, across the valley. The area where the tower is located has high altitude and steep slope, so the lightning cloud is easy to hit the transmission tower from the ridge. When the tower is installed in the mountain, the protection angle of the lightning wire in the downhill direction must form a larger angle. Therefore, the probability of lightning strike in the downhill stage is much higher than that in the uphill stage. As shown in Figure 2, there are three kinds of terrain that seriously affect the line shielding rate.

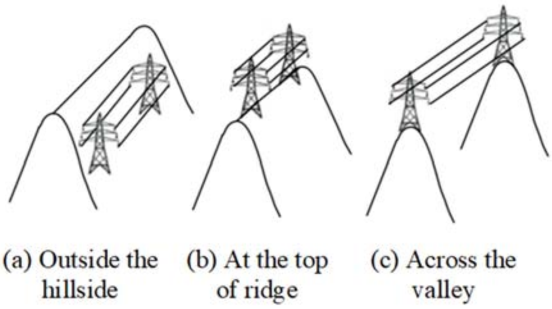

Figure 2. Tower erection method on basic terrain of mountainous area

Taking the trend of ridge and inclination as an example, due to the influence of inclination angle, the protective angle of lightning wire should be added on the ground inclination to expose the conductor on the side of the slope. Because the shielding rate of lightning in downhill stage is much higher than that in uphill stage, the arc increases. According to the statistical data of UHV level long-distance transmission lines, the shielding failure rate in mountainous areas is about 3 times higher than that in plain areas.

The terrain along the slope is shown in Figure 2(a). From the perspective of the electrical geometric model, the wire shielding situation is similar to that of the mountain top. For example, the slopes of the mountain slopes on both sides are θ_1 and θ_2, respectively. In the electrical geometry model, the ground inclination angles on both sides of the tower are θ_1 and θ_2, respectively. When the shielding situation is different on both sides of the tower conductor, the left side of the tower is similar to the top of the mountain, and the ground shields the conductor poorly. If the slope is θ, the ground inclination angle in the calculation of the electrical geometric model is θ. The situation on the right side of the tower is similar to that of the valley, and the wire is shielded by the ground better. If the slope is θ, the ground inclination angle in the calculation of the electrical geometric model is $-\theta$.

Table1. Shielding rate of 500 kV transmission line under complex mountainous areas. 1/(100km·a)

inclination angle θ	Outside the hillside	At the top of ridge	Across the valley
0°	0.46	1.4	0.05
10°	0.7	1.71	0.14
25°	1.48	2.35	0.28
30°	1.69	2.54	0.48

The ground inclination angle has a significant effect on the shielding rate of 500kV UHV transmission lines, which can be reasonably verified by the EGM. When the ground inclination angle is less than 10°, it has little effect on the shielding rate. But when the ground inclination angle is more than 10 °, the shielding rate is doubled. Therefore, when the ground inclination is large, smaller or even negative protection angle measures should be adopted to improve the lightning protection level of transmission lines. The probability of tower shielding failure is very small in flat ground, valley and climbing. However, once there is a large slope on the top of the mountain and along the slope, the shielding failure trip rate increases rapidly. The main cause of shielding failure is the weakening of ground shielding.

Figure 3 and Figure 4 show the trip rate of shielding failure when the slope of the mountain top is different from that along the slope. In both cases, the trip rate of shielding failure increases with the increase of the slope. When the slope is less than 20 ° The tripping rate of shielding failure is not significant with the increase of slope. But when the slope > 20 ° The tripping rate of shielding failure increases rapidly.

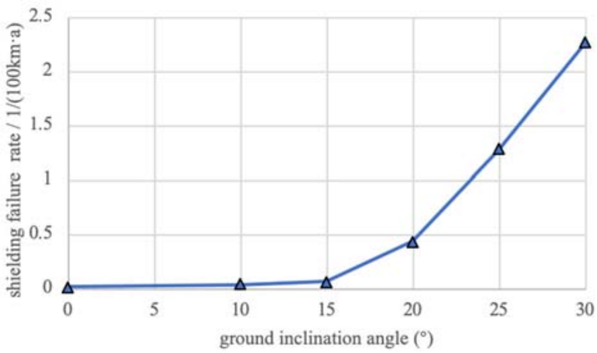

Figure 3. Shielding failure rate under different inclination angle at the mountain top

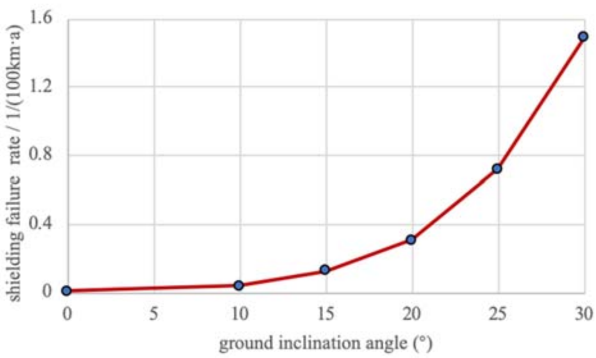

Figure 4. Shielding failure rate under different inclination angle outside the hillside

From the above analysis, it can be seen that shielding strikes are prone to occur on the top of the mountain, across the ditch, and along the outside of the slope. The shielding of the wire is formed by the lightning conductor and the ground. The weakening of the ground shielding effect increases the exposure arc of the wire and the shielding rate increases.

The ground inclination has a significant effect on the lightning shielding trip rate of 500kV UHV long-distance transmission lines, and the electrical geometric model can reasonably verify this phenomenon. When the ground inclination is less than 5°, it has little effect on the shielding rate. But when the ground inclination is > 20°, the shielding rate doubles. Therefore, when the ground inclination is large, a smaller or even negative protection angle should be adopted to improve the lightning protection level of the transmission line.

3 Conclusion

1) Based on the discharge characteristics of lightning and the structure of line tower system, the shielding effect of lightning conductor is analyzed by using the EGM. The ground inclination and installation angle of lightning conductor are comprehensively considered, and the shielding failure rate of the line is correlated with the lightning current.

2) There is a problem of high shielding failure trip out rate in climbing, valley and other terrain. It mainly occurs in the case of high tower, large slope of the mountain, along the slope and so on, which is caused by the poor shielding of the ground to the conductor.

3) The trip rate of shielding failure when the slope of the mountain top is different from that along the slope. In both cases, the trip rate of shielding failure increases with the increase of the slope. When the slope is less than 20° The tripping rate of shielding failure is not significant with the increase of slope. But when the slope > 20° The tripping rate of shielding failure increases rapidly.

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