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Calculation Method of Shielding Failure Trip-out Rate of Mountain Transmission Line

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Abstract: Due to limitations of the standard method, electrical geometry model, improved electrical geometry model and leader progress model in calculating the shielding failure trip-out rate, it adopts an improved calculation method, this method is based on the catenary equation and the formulas of shielding failure trip-out rate located at different positions of the mountain, the altitude and ground inclination of transmission corridor at any point along the span direction are taken full account, the actual height among the ground wire, the conductor wire and the ground and the angle of shade of transmission lines at any point are obtained, then uses MATLAB to develop applications to calculate the shielding failure trip-out rate of transmission lines at any point in any span with comparing the actual lighting data. Simulation and Calculation results verify the correctness of the improved calculation methods in this study. It provides a reliable basis for lightning protection design and renovation of overhead transmission lines under the high-altitude mountainous complex terrain conditions.

Key words: Shielding failure trip-out rate, mountainous areas, complex terrain, electric geometry model, MATLAB

INTRODUCTION

Power transmission line plays a very important role in power system, it is distributed in a vast and is vulnerable to be struck by lightning, especially in high altitude mountain area, more accidents are caused by a lightning strike (Zhang *et al*., 2004) and shielding failure is one of the major causes of transmission line fault. Therefore, studying the shielding failure problem of mountain transmission line can not only effectively prevent accidents caused by shielding failure, such as disconnection of the transmission line, transmission equipment damage and line trip but also plays a huge role in the safe and reliable operation of power systems and sustainable development of economy and society. This study takes a mountain 110 kV transmission line segment which is easy to be struck by lightning as an example and studies an improved method to calculate and analyze the shielding failure trip-out rate of transmission line from No. 46-48 tower. The improved calculation method uses MATLAB as a software development platform and is based on the electrical geometry model at different positions of mountain and the catenary equation. It takes full account of altitudes, ground inclinations and ground strike distance factor of transmission corridor at any point along the span direction to compute the shielding failure trip-out rate of transmission line at any point which is in any span and compares with the calculation results of the standard method and actual lightning faults, providing the feasible scheme for lightning protection design and improvement of transmission line under conditions of complex landscape in the high altitude mountainous area (Ma *et al*., 2011).

COMMON CALCULATION METHODS OF SHIELDING FAILURE TRIP-OUT RATE

Nowadays, the widely used calculation methods of shielding failure trip-out rate in engineering are mainly the standard method, electrical geometry model, improved electrical geometry model and leader progress model, but they all have some disadvantages.

The standard method, it is actually an empirical formula method which only divides the terrain into plains and mountains, ignoring the terrain and other factors on the impact of shielding failure trip-out rate, so its calculated results and the actual lightning situation have a larger difference. Electrical geometry model, improved electrical geometry model and leader progress model have some considerations for the terrain, but the ground inclinations, the actual heights among the ground wire, the conductor wire and the ground and the angles of shade of transmission line at any point used in the calculation are some fixed averages which can not clearly react the change of the terrain and shielding failure trip-out rate of transmission line at every point (Yin *et al*., 2012), so these four methods have some limitations.

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IMPROVED CALCULATION METHOD

Due to limitations of the above methods, an improved calculation method is proposed in this study. This method is based on the electrical geometry model at different positions of mountain, takes full account of altitudes, inclinations and ground strike distance factor of transmission corridor along the span direction at any point and uses the catenary equation to compute the actual heights among the ground wire, the conductor wire and the ground and the angles of shade of transmission line at any point, then putting the results into the corresponding formulas of mountain electrical geometry model to compute the shielding failure trip-out rate of transmission line at any point. Meanwhile, based on the above theory, we use MATLAB to develop applications which can compute the shielding failure trip-out rate of transmission line at any point which is in any span and is simple and flexible to synchronously calculate and simulate the shielding failure trip-out rate of single-circuit and multi-circuit transmission line of different towers. At the same time, in order to test the correctness of the calculation method, the improved calculation method and standard method are used to compute and contrast the shielding failure trip-out rate of all transmission towers, respectively in this study.

Shielding failure trip-out rate of transmission line at different positions of mountain

Shielding failure trip-out rate of transmission line on the side of the mountain: Sketch of electric geometry model of transmission line on the side of the mountain is shown in Fig. 1. r_g, r_s, r_c, h_s and h_c represent the ground striking distance, the ground wire striking distance, the conductor wire striking distance, the average height of the ground wire and the average height of the conductor, respectively. θ and α represent the ground inclination of mountain and the angle of shade of ground wire. d_{CL} and d_{CR} represent the exposure distance of the left and right of transmission line, respectively.

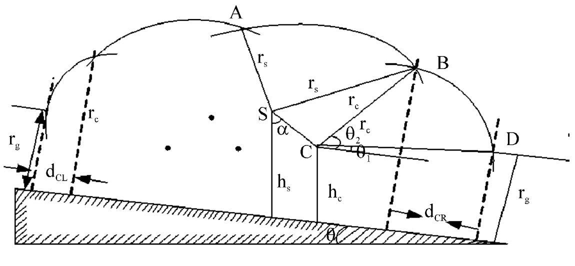

Fig. 1: Sketch of electric geometry model of transmission line on the side of the mountain

The left shielding failure trip-out rate of transmission line-S_{FTRL}, the right shielding failure trip-out rate of transmission line-S_{FTRR}, the total shielding failure trip-out rate of transmission line-S_{FTR} can be computed by the following Eq. 1 (Li *et al*., 2010a):

$$\begin{cases} S_{FTRL}=N_g l?\int_{I_c}^{I_{maxl}} d_{CL}(I)f(I)dI \\ S_{FTRR}=N_g l?\int_{I_c}^{I_{maxR}} d_{CR}(I)f(I)dI \end{cases} \quad (1)$$
$$S_{FTR}=S_{FTRL}+S_{FTRR}$$

In Eq. 1, N_g and l, respectively the lightning density and the length of transmission line, I_{max} and I_c, respectively the maximum shielding lightning current and the critical flashover current. d_{CL} and d_{CR} can be calculated by the following Eq. 2, f(I) can be calculated by the following Eq. 3, I_{max} and I_c can be calculated by the following Eq. 4:

$$\begin{cases} d_{CL}(I)=r_c(\cos?_1-\cos?_{2L}) \\ d_{CR}(I)=r_c(\cos?_1-\cos?_{2R}) \end{cases} \quad (2)$$

$$f(I)=0.026*10^{-0.011I} \quad (3)$$

$$\begin{cases} I_{maxL}=(0.1*r_{smL})^{1.54} \\ I_{maxR}=(0.1*r_{smR})^{1.54} \end{cases} I_c=\frac{U_{50\%}(2Z_0+Z_c)}{2Z_0Z_c} \quad (4)$$

In Eq. 2, θ_1, θ_{2L}, θ_{2R} and r_c can be shown by the following Eq. 5. In Eq. 4, r_{smL} and r_{smR} can be calculated by the following Eq. 6:

$$\begin{cases} ?_1=\arcsin\left[(r_g-h_c\cos?)/r_c\right] \\ ?_{2L}=\frac{p}{2}+(a-?)-\arccos\left(\frac{r_c^2+d_{sc}^2-r_s^2}{2r_cd_{sc}}\right) \\ ?_{2R}=\frac{p}{2}+(a+?)-\arccos\left(\frac{r_c^2+d_{sc}^2-r_s^2}{2r_cd_{sc}}\right) \end{cases} \quad (5)$$
$$r_c=10I^{0.65}$$

$$\begin{cases} r_{smL}=\left[ß(h_s+h_c)+\sin(a-?)\sqrt{(h_s+h_c)^2-G_L}\right]\frac{\cos?}{2F_L} \\ r_{smR}=\left[ß(h_s+h_c)+\sin(a+?)\sqrt{(h_s+h_c)^2-G_R}\right]\frac{\cos?}{2F_R} \end{cases} \quad (6)$$

In Eq. 5, d_{SC} is the length from the point S to C and r_g is can be determined by the following Eq. 7 (Zhou *et al*., 2012):

$$\begin{cases} r_g=\left[3.6+1.7\ln(43-h_c\cos?)\right]I^{0.65}, h_c\cos?<40\text{ m} \\ r_g=5.5I^{0.65}, h_c\cos?>40\text{m} \end{cases} \quad (7)$$

In Eq. 6, β is the striking distance coefficient, it is can be determined by the following Eq. 8, F_L, F_R, G_L and G_R can be determined by the following Eq. 9 (Xie *et al.*, 2009):

$$\begin{cases} ß=0.36+0.17\ln(43-h_c),h_c>40\text{ m} \\ ß=0.55,h_c>40\text{ m} \end{cases} \tag{8}$$

$$\begin{cases} F_L=ß^2-\sin^2(a-?) \\ F_R=ß^2-\sin^2(a+?) \end{cases} \begin{cases} G_L=F_L\left[(h_s-h_c)/\cos a\cos ?\right]^2 \\ G_R=F_R\left[(h_s-h_c)/\cos a\cos ?\right]^2 \end{cases} \tag{9}$$

Shielding failure trip-out rate of transmission line on the top of the mountain: Sketch of electric geometry model of transmission line on the top of the mountain can be shown in Fig. 2. θ_L and θ_R represent the ground inclination of the left and right of mountain, respectively. Shielding failure trip-out rate of transmission line on the top of the mountain can be also computed by the following Eq. 1; d_{CL} and d_{CR} can be calculated by the following Eq. 10:

$$d_{CL}(I)=d_{CR}(I)=r_c(\cos ?_1-\cos ?_2) \tag{10}$$

where, θ_1 and θ_2 can be shown by the following Eq. 11:

$$\begin{cases} ?_1=\arcsin\left[(r_g-h_c\cos ?_R)/r_c\right] \\ ?_2=\dfrac{p}{2}+(a+?_R)-\arccos\left(\dfrac{r_c^2+d_{sc}^2-r_s^2}{2r_cd_{sc}}\right) \end{cases} \tag{11}$$

In this model, r_{smL} and r_{smR} should be calculated by the following Eq. 12 (Chen *et al.*, 2003):

$$\begin{cases} r_{smL}=\left[ß(h_s+h_c)+\sin(a+?_L)\sqrt{(h_s+h_c)^2-G_L}\right]\dfrac{\cos ?_L}{2F_L} \\ r_{smR}=\left[ß(h_s+h_c)+\sin(a+?_R)\sqrt{(h_s+h_c)^2-G_R}\right]\dfrac{\cos ?_R}{2F_R} \end{cases}$$
$$\begin{cases} F_L=ß^2-\sin^2(a+?_L) \\ F_R=ß^2-\sin^2(a+?_R) \end{cases} \tag{12}$$
$$\begin{cases} G_L=F_L\left[(h_s-h_c)/\cos a\cos ?_L\right]^2 \\ G_R=F_R\left[(h_s-h_c)/\cos a\cos ?_R\right]^2 \end{cases}$$

Shielding failure trip-out rate of transmission line set up from the foot to the top of mountain: Sketch of electric geometry model of transmission lines set up from the foot to the top of mountain can be shown in Fig. 3. θ represents the ground inclination of mountain. In this model, shielding failure trip-out rate of transmission line should be calculated by the following Eq. 13:

$$S_{FTR}=2N_gl?\int_{I_c}^{I_{max}} d_C(I)f(I)dI \tag{13}$$

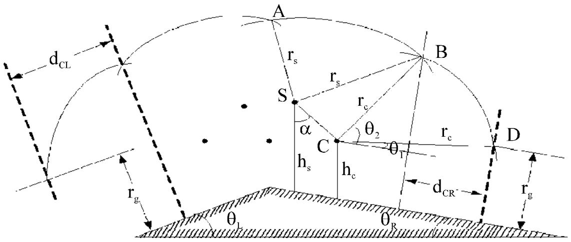

Fig. 2: Sketch of electric geometry model of transmission line on the top of the mountain

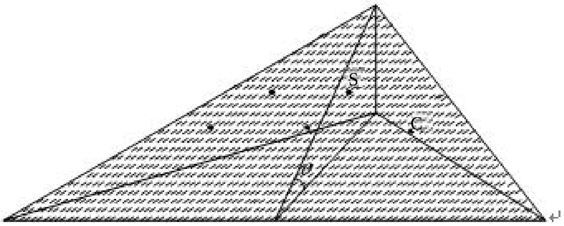

Fig. 3: Sketch of electric geometry model of transmission lines set up from the foot to the top of mountain

In this model, dc(I) can be also calculated by the following Eq. 10, θ_1 and θ_2 in the dc(I) can be shown by the following Eq. 14. I_{max} can be shown by the following Eq. 15:

$$\begin{cases} ?_1=\arcsin\left[(r_g-h_c\cos ?)/r_c\right] \\ ?_2=\dfrac{p}{2}+(a+?)-\arccos\left(\dfrac{r_c^2+d_{sc}^2-r_s^2}{2r_cd_{sc}}\right) \end{cases} \tag{14}$$

$$I_{max}=(0.1*r_{sm})^{1.54} \tag{15}$$

where, the maximum striking distance r_{sm} can be shown by the following Eq. 16 (Zhang *et al.*, 2005):

$$r_{sm}=\left[ß(h_s+h_c)+\sin a\sqrt{(h_s+h_c)^2\cos^2 ?-G}\right]/2F$$
$$\begin{cases} F=ß^2-\sin^2 a \\ G=F\left[(h_s-h_c)\cos ?/\cos a\right]^2 \end{cases} \tag{16}$$

Calculation of the actual height among the ground wire, the conductor wire and the ground and the angle of shade of transmission line at any point: The feature of this improved method is that using the actual heights among the ground wire, the conductor wire and the ground and the angles of shade of transmission line at any point to replace these corresponding averages of shielding failure trip-out rate formulas of transmission line at different positions of mountain to improve the accuracy of shielding failure trip-out rate.

Calculation of the actual height among the ground wire, the conductor wire and the ground: If the terrain of transmission line corridors and the suspension mode of the wire are shown in Fig. 4, the actual height among the conductor wire and the ground at any point C can be calculated by the following Eq. 17 (Li *et al.*, 2011):

$$h_c = H_{A'} + H_{AL} - d_1 - H_{C'} \tag{17}$$

In Eq. 17, $H_{A'}$ is the altitude of the left tower, $H_{C'}$ is the altitude of surface projection of any point C on the wire, H_{AL} is the height of wire's hanging point of the left tower, d_1 is the height difference from any point C on the wire to the wire's hanging point. Therefore, we can get the Eq. 18 by the catenary equation (Li *et al.*, 2010b):

$$d_1 = \frac{4Fx_A(l'-x_A)}{l'^2} - \frac{4Fx_A(l'-x_c)}{l'^2} \tag{18}$$

where, l and l' represent the actual span and the equivalent span, respectively; x_A and x_C represent the abscissa of the point A and C, respectively; F represents the conductor sag of the equivalent span.

Similarly, we can get the calculation of the actual height among the ground wire and the ground at every point by the calculation of the actual height among the conductor wire and the ground, it is shown by the Eq. 19:

$$h_s = H_{A'} + H_{BL} - d_2 - H_{C'} \tag{19}$$

And the method for solving d_2 is the same with the method for solving d_1.

Calculation of the angle of shade of transmission line at any point: For the angle of shade of transmission line at any point, we can use the Eq. 20 to compute them:

$$a = \arctan\left(\frac{\overline{sc}}{d'}\right) \tag{20}$$

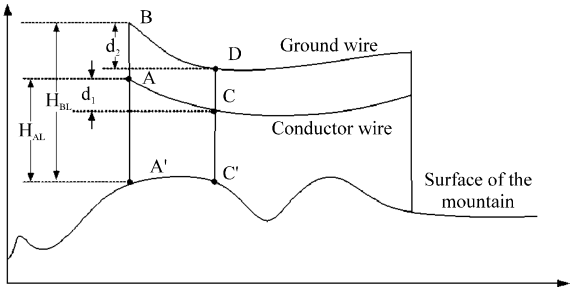

Fig. 4: Sketch about the terrain of tower

And d' is the height difference of the conductor wire and the ground at any point; $\overline{sc}$ is the horizontal distance of the conductor wire and the ground at any point.

EXAMPLE ANALYSIS

Line parameters: The terrain of Luanchuan is complex, it has awful weather and high soil resistivity and the transmission line corridor is mostly mountainous. This study takes a mountain 110 kV transmission line segment which is easy to be struck by lightning as an example. The whole length of transmission line is 39.73 km, wire is LGJ-300, the length of corresponding sag is 5.3 m, lightning line is GJ-50, the length of corresponding sag is 2.8 m and ground line is OPGW. The whole transmission line has 96 towers, 85% of the towers are located in the high mountain and 50% of which are located in the mining area. The main tower types in this line can be shown by the Fig. 5 and 6. This study takes the spans from No. 46-48 tower as an example, calculates and analyzes the shielding failure trip-out rate of transmission line (Cao *et al.*, 2010). Wherein, the topographic map of transmission corridors can be shown in Fig. 7 and the ground inclinations of transmission corridors can be shown in Fig. 8.

Calculation of shielding failure trip-out rate of transmission line from No. 46-48 tower: This study adopts the improved method and uses MATLAB as the software platform to develop applications to compute shielding failure trip-out rate of transmission line at every point from No. 46-48 tower, the calculation diagram of this application can be shown in Fig. 9 and the calculation results of shielding failure trip-out rate of transmission line at every point from No. 46-48 tower can be shown in Fig. 10.

Validation of improved calculation method: In order to verify the correctness and engineering feasibility of improved calculation method, This study still takes a mountain 110 kV transmission line segment which is easy to be struck by lightning as an example, it separately uses the standard method and the improved calculation method computing the shielding failure trip rate of all towers in this line, the results are shown in Fig. 11 and 12.

Through the Fig. 11 and 12, it shows that the trend of results by the standard method and that by the improved calculation method are basically similar. Meanwhile, statistics shows that the towers which suffered from Shielding failure, respectively No. 47, 63 and 88 in the last year and these three towers all have high shielding failure trip rate in the Fig. 11 and 12. So, it can be proved that the

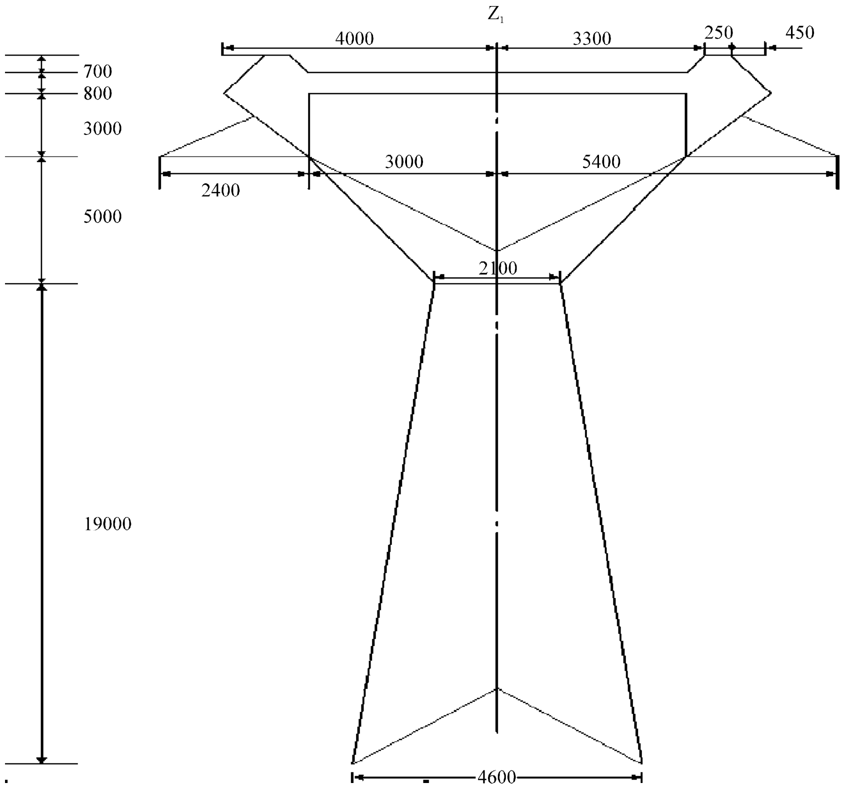

Fig. 5: Size of Z1 linear tower

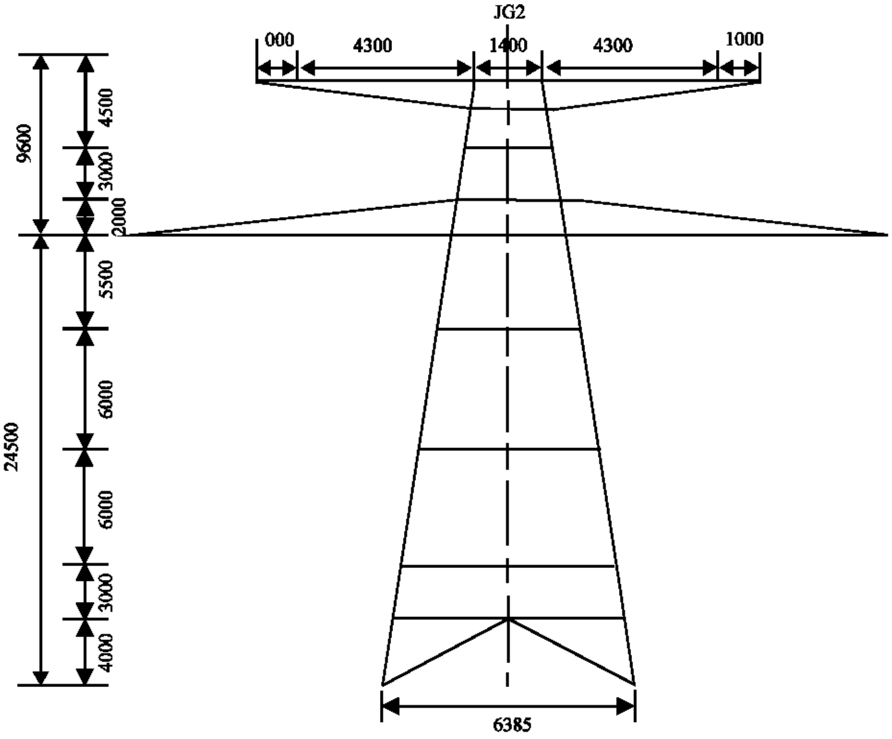

Fig. 6: Size of JG2 strain tower

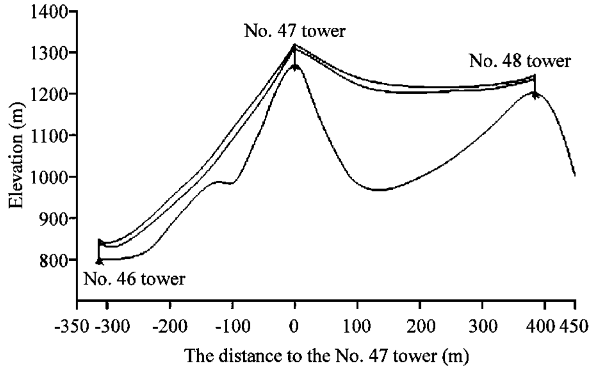

Fig. 7: Topographic map of transmission corridors of from No. 46-48 tower

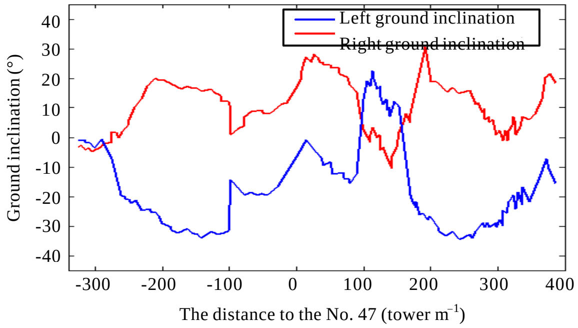

Fig. 8: Ground inclinations of transmission corridors from No. 46-48 tower

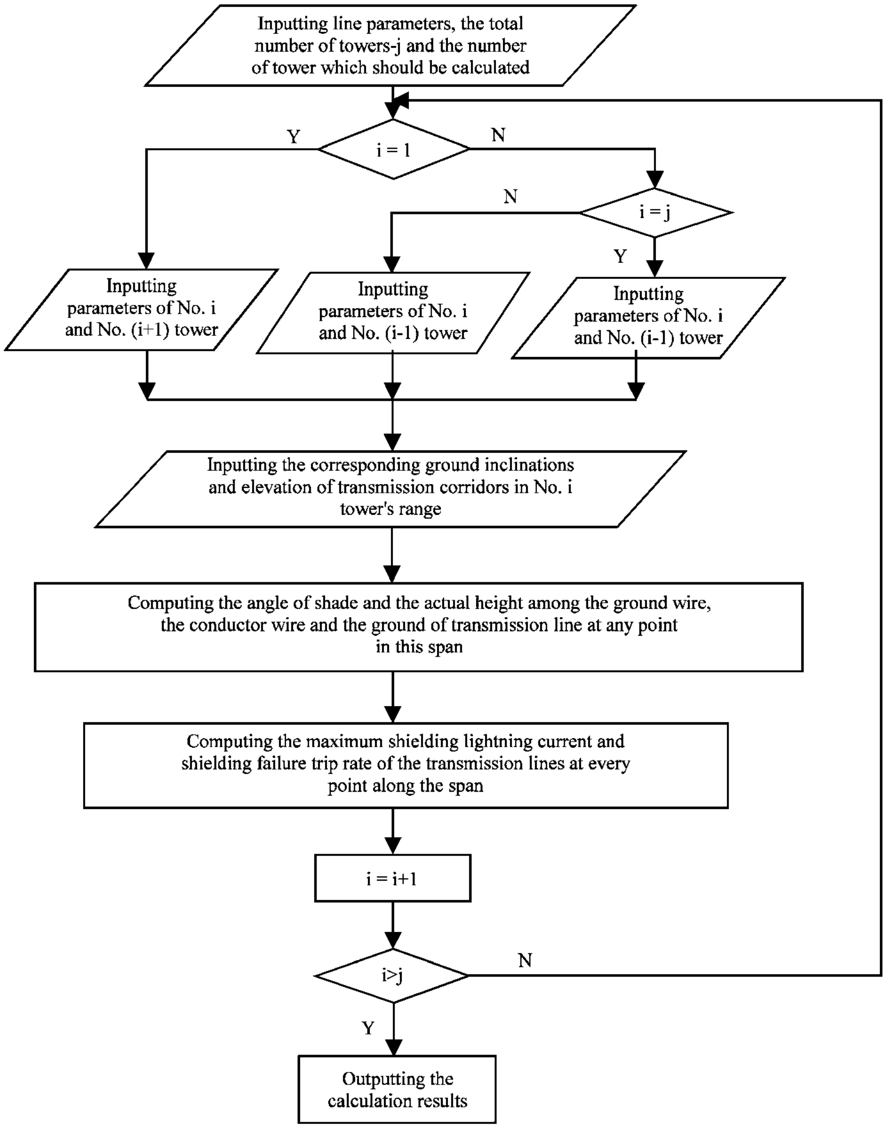

Fig. 9: Calculation diagram of Shielding failure trip rate program of the transmission lines

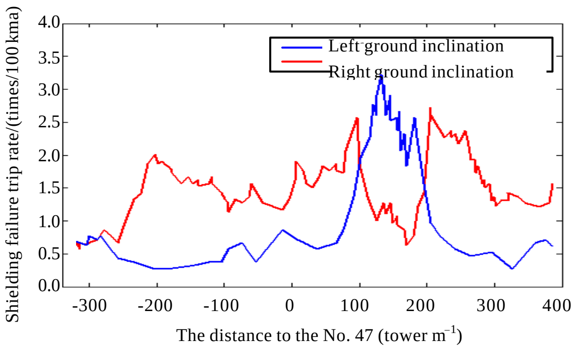

Fig. 10: Shielding failure trip rate of the transmission lines at every point from No. 46-48 tower

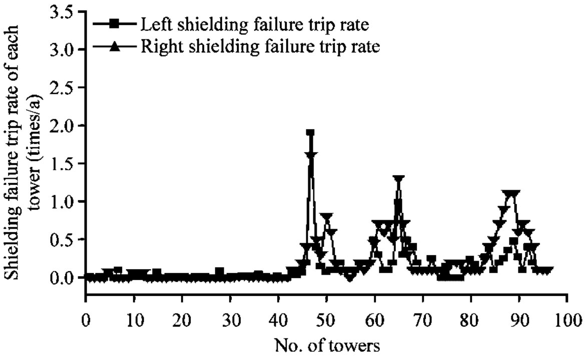

Fig. 11: Shielding failure trip rate of towers by the standard method

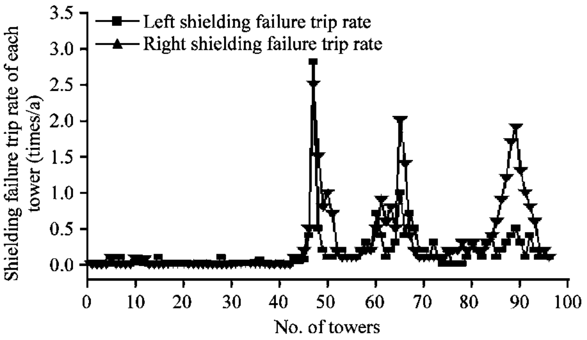

Fig. 12: Shielding failure trip rate of towers by the improved calculation method

improved calculation method is correct and feasible in engineering by the analysis and comparison of the results of the above.

CONCLUSION

- Studying an improved calculation method, it uses MATLAB as a software development platform, letting the calculation more convenient; it is based on the electrical geometry model at different positions of mountain, this model is more accurate than traditional electrical geometry model; It takes full account of altitudes, ground inclinations and ground strike distance factor of transmission corridor along the span direction at any point, the calculation results are more accurate and reliable comparing with the results of only bring some corresponding averages to the traditional electrical geometry model. At the same time, this improved method can compute the shielding failure trip-out rate of transmission line at any point which is in any span, but other methods can simply get the shielding failure trip-out rate of the entire line. So this improved calculation method can be accurate, clear and convenient to compute the shielding failure trip-out rate of transmission line at any point which is in any span and provides more targeted basis for lightning protection design and renovation
- Simulation results of this study show that the results of this improved method are not only similar with the results of the standard method, but also coincide with the lightning failures in actual operation, so the improved method can be largely proved to be correct and effective

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