A Multi-dimensional Analysis Method for the Tripping Risk of Lightning Winding Across the Transmission Line

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Abstract. Trip to cope with the lightning strike caused around power grid, this paper proposed a transmission line based on the mechanism of lightning strike around all lightning strike tripping around risk analysis method. This method needed to detour lightning tripping thunderstorms and risk analysis of transmission lines tower size, proportion of topography, altitude, insulation configuration data were collected, calculated in turn hit distance, distance and exposure correction of line pressure level and single-base tower above factors lightning strike risk. Based on the calculation model, the lightning wind characteristics under different tower shout height, lightning day and terrain were studied to identify the weak links along the line. Select the composition condition calculation of typical tower lightning strike tripping around risk, based on the same area across the terrain and tower usage of extract weight coefficient calculation all lightning strike tripping around risk, through the typical combination of the weighted average of all lightning strike tripping around risk was analyzed. Through the example analysis, verified the feasibility of this method to improve the reliability of transmission lines.

Keywords: Lightning winding; Multi-dimensional analysis; Risk assessment; Factor weight analysis.

1. Introduction
In recent years, China's electricity demand has been increasing year by year, and transmission line construction projects are gradually increasing. The distribution of transmission lines is staggered, which makes them vulnerable to the influence of various factors in the process of operation and causes various electrical safety accidents. Among them, electric power accidents caused by lightning around are frequent, so lightning protection treatment of transmission lines is very necessary.

At present, the evaluation methods based on lightning winding model of transmission lines include regulation method, electrical geometric model method, and pilot model method. The protocol method is an empirical formula for calculation of transmission line winding based on years of grid operation experience and small-scale discharge test results[1]. However, the conventional protocol method has a large error in calculating the probability of lightning winding of transmission lines. Leader Developing Model (LPM) is a model proposed by Risk [2]. The Leader Developing Model method can better explain the nature of the circumferences phenomenon and has certain physical significance. However, the solution results of the pilot development model method are highly sensitive to the relevant parameters.
in the model, and the variation of parameters has a great influence on the calculation results. The electric geometric model method integrates the physical principle of lightning strike and the data of power grid operation [3-4]. The strike distance coefficient in the model is the key to improve the performance of the model, which can be continuously optimized to improve the effectiveness and accuracy of the model. Compared with the other two methods, the electrical geometric model method has more advantages in accuracy and effectiveness, and many scholars have adopted this method. Literature 4 studied the difference of trip rate of wound trip when considering different temperatures in the electrical geometric model, and found that the trip rate of wound trip approximately decreases linearly with the increase of temperature [5]. Eriksson used the CIGRE transmission line trip statistics to verify the rationality of the improved electrical geometry model when he established the improved electrical geometry model [6]. This paper proposed a risk of transmission line lightning strike tripping around all of multidimensional analysis method, is a kind of electrical geometric model method. It fully considering the topography, altitude, adopt protection angle, high terrain, tower, thunder and lightning, the four dimensions of a typical combination, extract the weight coefficient of wide range of lightning strike tripping around risk quantitative analysis and has good accuracy and objectivity.

2. Analysis on the Risk Parameters of Lightning Circuit
Based on the dimension parameters, insulation configuration, monitored thunderstorm day and average altitude of the main tower head in line, the protection angle, strike distance and the modified insulator facticity voltage are calculated and analysed respectively.

2.1. Analysis of Ground Protection Angle
The spatial position relationship between ground wire and ground wire protection angle is determined by the distance between pole and tower cross arms, cross arm length, and ground wire support insulator string configuration. The calculation formula is as follows:

\[ \theta = \arctan \left( \frac{S_e - S_{gw}}{h_1 + h_2 - l_i + l_c} \right) \]

\( S_e \) is the length of traverse arm; \( S_{gw} \) is the horizontal arm length of ground wire; \( h_i \) is the distance between traverse and ground support; \( h_2 \) is the height of ground wire bracket; \( l_i \) is the string length of ground wire; \( l_c \) is the wire string length.

2.2. Blow from the Analysis
Strike distance refers to the critical breakdown distance between the lightning charge leader head in the air and the ground and the object on the ground. The strike distance of the conductor, ground wire and the ground can be calculated by the following formula:

\[ r_s = 10I^{0.65}, \quad r_c = 1.63(5.015I^{0.578} - 0.001U_{dc})^{1.125} \]

\[ r_g = \begin{cases} 
[3.6 + 1.7 \ln(43 - h_{av})]I^{0.65}, & h_{av} < 40m \\
5.5I^{0.65}, & h_{av} \geq 40m 
\end{cases} \]

\( r_s \) is the strike distance between the leader and the ground, m; \( I \) is lightning current amplitude, kA; \( r_c \) is the strike distance between the leader and the conductor, m; \( U_{dc} \) is the voltage class of the transmission line, kV; \( r_g \) is the striking distance between the leader and the earth, m; \( h_{av} \) Mean height of conductor to ground, m.

Among them, the lightning current amplitude probability recommended in GB/T50064-2014 "Over-Voltage Protection and Insulation Coordination of AC Electrical Devices" is calculated as follows: [7]

When the thunderstorm day is greater than 20 days

\[ P(I_0 \geq I_0) = 10^{-5} \]

When the thunderstorm day is less than 20 days

\[ P(I_0 \geq I_0) = 10^{-4} \]
$P(I_i \geq I_0)$ is the probability that the lightning current amplitude exceeds $I_0$.

2.3. Analysis of Insulator Flashover Voltage

Insulator flashover voltage is a key index to judge whether flashover tripping occurs. When insulation performance is good enough, it can withstand lightning impact without flashover. Meanwhile, insulator flashover voltage is affected by altitude, and altitude correction factor is introduced:

$$U_{50\%} = \frac{1}{(533 + 132) \frac{1}{1.1 - \frac{H}{10000}}}$$

$L$ is the dry arc distance of the insulator, km; $H$ is the altitude, km, and $U_{50\%}$ is the absolute value of 50% flashover voltage of the insulator.

3. Multi-dimensional Analysis Method for Lightning Trip Risk around the Whole Transmission Line

From the angle of protection, high terrain, tower, thunder and lightning, the four dimensions set analysis group. According to the line parameters, the multi-dimensional typical combination can be extracted to analyze the risk value of lightning circuit in each case, and the method of flow chart shown in figure 1.

![Figure 1. Method flow chart.](image-url)

Step 1: Extract the dimension parameters, insulation configuration, monitored thunderstorm day and average altitude of the main tower heads in line, calculate the protection angle, strike distance and the corrected insulator flashover voltage;

Step 2: Set up an analysis group from four dimensions, namely, protection angle, terrain, tower height and lightning day, and calculate the risk value of lightning winding circuit in each case based on the transmission line shielding principle.

Step 3: Combined with the calculation results in Step 2, the main factors affecting the lightning wind risk of this line are analysed. Combined with the terrain proportion or protection angle setting information collected from the existing transmission lines, the main representative tower protection angle, terrain, tower height and lightning day combination are selected.

Step 4: Based on the topographic proportion of the whole line in the same area and the use of the tower, extract the weight of the typical combination of tower protection angle, terrain, tower height and lightning day selected from Step 3, and conduct quantitative analysis on the lightning trip risk around the whole line.

According to the occurrence mechanism of lightning around the lightning circuit, the incidence angle is randomly distributed when the lightning charge leader develops near the circuit. The following formula is used to fit the probability distribution of lightning incidence angle:

$$g(\psi) = K_m \cos^n(\psi)$$

$g(\psi)$ is the probability of lightning charge pilot angle of incidence for $\psi$; $K_m$ is the normalized coefficient, which needs to be satisfied.
Lightning occurs when the lightning charge leader is in the exposed arc of the wire. For a circle with a conductor as the center and a conductor strike distance as the radius, the exposed arc can be obtained under the control conditions of ground wire protection and ground strike distance protection. Then, the exposed distance of the conductor can be calculated according to the following formula:

\[
X = \int_{0}^{\theta} \int_{\varphi}^{\psi(\theta)} g(\psi) \cos(\psi) d\psi d\theta
\]  

(8)

\(\theta\) is the horizontal angle between the geodetic protection area and the intersection point of the traverse exposure circle, \(\varphi\); \(\psi(\theta)\) is the horizontal angle between the intersection point of the wire exposure circle and the ground wire protection range, \(\varphi\); \(\psi(\theta)\) is the minimum angle of lightning charge that can hit the leader, \(\varphi\); \(\psi(\theta)\) is the maximum angle of lightning charge that can hit the leader, \(\varphi\).

The lightning insulation level of the line insulation is analyzed by using the lightning equivalent circuit in parallel with the lightning channel wave impedance after using the lead wave impedance series line voltage source. The lightning voltage applied on the discharge channel at the moment of winding is calculated according to the following formula:

\[
U_A = \frac{Z_Z}{Z + 2Z_Z} \left( IZ + 2U_{ac} \right)
\]  

(9)

\(Z\) is the conductor wave impedance, \(\Omega\); \(Z_Z\) is lightning channel wave impedance, \(\Omega\); \(I\) is the lightning current amplitude, kA; \(U_{ac}\) is the voltage of the transmission line to the ground, kV; \(U_A\) is the lightning voltage on the discharge channel, kV.

There is a correspondence between the lightning channel equivalent wave impedance and the lightning current amplitude. After the lightning current amplitude is determined, \(Z_Z\) can be obtained according to the lightning channel equivalent wave impedance and the lightning current amplitude characteristic curve. According to the winding occurrence criterion, the lightning resistance level can be calculated when the winding occurs when \(U_A \geq U_{50\%}\):

\[
I_A \geq \frac{Z + 2Z_Z \left( U_{50\%} - \frac{2Z_Z U_{ac}}{Z + 2Z_Z} \right)}{ZZ_Z}
\]  

(10)

The risk value of lightning winding circuit in each case in a typical combination is calculated by the following formula:

\[
SFF = \frac{2N_x}{10} \int_{c}^{\text{max}} XP(I) dl
\]  

(11)

\(N_x\) is the ground flash density of the region, Time/(a·km²); \(X\) is the exposure distance of the wire, km; \(I\) is the lightning current amplitude, A; \(I_{\text{max}}\) is the lightning resistance level of the transmission line, A; \(I_{\text{max}}\) is the upper limit value of lightning current amplitude, A.

The risk values of lightning around the lines under all conditions in the typical combination were sorted to obtain the high-risk typical combination. The weak links in line with the height of the pole tower, the terrain, the thunderstorm day and the protection angle were similar to the high-risk typical combination. Lightning protection measures were additionally set.

Since the landform of the tower construction has been fixed, and the combined ratios of the four dimensions of full-line protection angle, terrain, tower height and lightning day are fixed, the weight coefficient can be extracted based on the full-line terrain ratio, tower use and protection angle setting, and the lightning wind risk of all-line can be calculated according to the following formula.

\[
SFF^{\alpha}_{h_i} = \sum_{j=1}^{4} \beta_j \left( \sum_{k=1}^{4} \sigma_{\alpha SFF^{\alpha}_{h_i}} \right)
\]  

(12)

\(h_i\) is the height of the J type tower, m; \(\beta_j\) is the proportion of the tower with a height of \(h_i\); \(SFF^{\alpha}_{h_i}\) is the lightning wind risk when the protection angle is \(\theta\); the height of the tower is \(h_i\), and the ground
inclination is $i$; $\alpha$ is the proportion of terrain section in the whole line when the ground dip angle is $i$; $S_{FF}$ is the risk of lightning winding across the line.

4. Case Study

According to some statistics, from 2010 to 2019 of power grid based on protection angle, high terrain, tower, thunder and lightning, the four dimensions of a typical combination, and calculation of all cases in typical combination of lightning strike lines around the risk value and sorted by size, by typical combination, risky high-risk combination of typical sections of line lightning protection circuit for additional Settings. At the same time, the weight coefficient is extracted based on the condition of the whole line, and the risk of lightning winding is analyzed.

The thunderstorm control day is 40 days and the protection angle is 14°. The lightning wind risk under different tower heights with ground dip angles of 0°, 10°, 20° and 30° is analyzed, and the characteristics of tower height and lightning wind risk are obtained, as shown in Figure 2.

As can be seen from the figure, the risk of lightning winding gradually increases as the height of the tower increases, and as the slope of the ground increases, the risk of lightning wind gradually increases.

The control ground angle was 20°, the protection angle was 14°, and the lightning winding risks under different thunderstorm days were analyzed under the condition that the tower height was 37m, 40m, 43m and 46m. The characteristics of lightning winding risks on thunderstorm days and lightning winding risks were obtained, as shown in Figure 3.

![Figure 2. Influence of tower height and ground inclination on lightning shielding risk.](image2)

![Figure 3. Influence of thunderstorm day on lightning shielding risk.](image3)

It can be seen from the figure that with the increase of thunderstorm days, the risk of lightning winding increases. The lightning winding risk of the existing full line is calculated, and the lightning winding risk of the whole line under different protection angles is analyzed. The calculation results are shown in Figure 4. According to the calculation results of lightning wind risk based on the typical combination of four dimensions, namely tower height, terrain, thunderstorm day and protection angle, and according to the operation and maintenance monitoring data provided by the line department, the tower weight table and terrain weight table with a full line thunderstorm day of 40 days/year and a wire protection angle of 14° are shown in Table 1 and Table 2.

![Figure 4. Influence of thunderstorm day on lightning shielding risk.](image4)
Table 1. Tower height weight.

| Tower height/m | Weight/% |
|----------------|----------|
| 37             | 93.9     |
| 40             | 6.1      |
| 43             | 0        |
| 46             | 0        |

Table 2. Terrain weight.

| Ground inclination/° | Corresponding topography                      | Weight/% |
|---------------------|-----------------------------------------------|----------|
| 0                   | River network swamp topography                 | 11.03    |
| 10                  | Flat terrain                                   | 16.22    |
| 20                  | Mountainous terrain                            | 32.65    |
| 30                  | High mountains and mountains                   | 40.10    |

Based on the weight analysis, the lightning wind risk of different protection angles across the whole line is quantitatively analyzed, as shown in Figure 4. It can be seen from the figure that with the increase of protection angle, lightning wind risk increases. The multi-dimensional risk assessment method can be used to quantify the lightning wind risk in different states, and it can be used as a reference for line operation, maintenance and dispatching, which has certain practical basis.

5. Conclusion

Compared with other methods, the risk analysis method proposed in this paper takes into account the influence of elevation correction and topography, and considers factors more comprehensively. It analyzes the tower height, terrain, thunderstorm and high-risk typical protection Angle combination, to identify all the weak link, to avoid tower analysis for all of the huge amounts of calculation, fast through the typical combination of the weighted average of all lightning strike tripping around risk analysis more accurate, to line lightning protection provide effective Suggestions

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