Analysis of shielding failure flash-over rate of collection lines of wind farms in mountainous areas

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Abstract. Aiming at the current situation of serious economic losses caused by lightning shielding on the collection lines of wind farms in mountainous areas. First, this paper uses the horizontal section location map of the collection line to extract the terrain parameters, Then use the catenary equation to determine the spatial position of the conductor and ground of any section of the collector line along the pitch direction, and obtain the height of the conductor and the ground to the ground. Finally, complete the modeling calculation analysis of the three-dimensional electrical geometry model (EGM) of the entire collection line. The calculation results show that, when the thunderstorm day, the arrangement of the collection line and the structure of the tower are the same, the SFFOR of the collection line of the wind farm in mountainous terrain is 0.487 times/100 km/year, and the plain terrain is 0.167 times/100 km/year, that is, mountainous area is 2.9 times of plain terrain; It is recommended to use double lightning protection poles with small protection angles on the collection lines of wind farms in mountainous areas, or install lightning arresters for poles that are prone to flashover to meet the design requirements of line lightning protection.

1. Introduction

According to industry statistics, China’s accumulated wind power installed capacity was 210 million kilowatts, of which onshore wind power has accumulated 204 million kilowatts by the end of 2019 [1]. It has become the world’s largest wind power market, with the rapid development of the wind power industry, the onshore wind farms in mountainous or high-altitude areas, the problem of lightning tripping faults in their collection lines is becoming more and more prominent. The collection line of a wind farm is an important way to collect and transmit the electric energy generated by the wind turbine to the booster station, and its voltage level is generally 35kV. Relevant data shows that in the past two years, the collection line of a wind farm in a mountainous area has tripped up to 20 times due to lightning faults, causing direct economic losses of more than 3 million yuan in electricity. Due to the complex geographical environment in mountainous areas, the height of the towers at the initial stage of the line design is generally close to or higher than 110kV transmission lines, and the towers structure are mostly
single lightning protection lines or towers with larger protection angles. Therefore, the collection line located in the strong lightning activity area faces a higher risk of lightning shielding failure.

At present, most of the research on the SFFOR is concentrated on high-voltage transmission lines. By considering various factors such as lightning incident angle, wind speed, topography, transmission line tower structure, etc., the improved electrical geometric model is used to evaluate and analyze the shielding failure risk of transmission lines, and a series of practical suggestions are proposed[2-5]. The collection line of wind farms often aggregates multiple wind turbines and is erected along with the distribution of wind turbines. First of all, due to the particularity of the wind power industry, most people in the industry are mainly concerned about the operation status of wind turbines in wind farms; secondly, in the initial stage of collecting circuit design, engineers’ considerations for lightning protection of collection circuits are generally based on the current design specifications for transmission lines at the same voltage level; finally, collection lines are often erected in mountainous areas along with a single wind farm, and generally only research workers related to wind power will focus on this. Therefore, in the current related literature, it is rare to see the analysis of the lightning trip fault of the collection line, especially the SFFOR.

First, this paper uses the more mature three-dimensional EGM calculation method in the calculation of the SFFOR of transmission lines, extracts the topographic parameters through the horizontal section location map, and compiles the calculation program that can consider the topographic factors; then it analyzes the relationship between the SFFOR, altitude, and the topography of the current collection line, and compare the changes in the SFFOR under plain terrain; finally, it evaluates the lightning shielding risks faced by power collection lines erected in mountainous terrain, and proposes lightning protection engineering recommendations that should be considered at the initial stage of collection line design.

2. Calculation Method of 3D Electrical Geometric Model

The electrical geometric model (EGM) is commonly used in the calculation of SFFOR performance of transmission lines, and its model is shown in Fig.1.

According to "IEEE Guide for Improving the Lightning Performance of Transmission Lines", this article uses the following formulas to calculate the SFFOR.

\[ r_s = r_c = 10^{0.06} \]  
\[ r_g = k r_s \]  
\[ k = \begin{cases} 0.36 + 0.17 \ln (43 - h_c), & h_c < 40m \\ 0.55 & h_c \geq 40m \end{cases} \]

where
\( r_s \) is the striking distances to the shield wire; \( r_p \) is the striking distances to the phase conductor; \( h \) is the striking distances to earth. 

If a downward leader, having a prospective current \( I \) for which the arcs were dawn, touches the arcs between B and D, the leader will strike the phase conductor. If the leader touches between A and B, it will strike the shield wire. If all leaders are considered vertical, the exposure distance for a shielding failure is \( l_{BD} \).

\[
S_{SFFOR} = 0.1N_e \int_{l_c}^{l_{BD}} f(I) dI
\]  

(4)

where

- \( N_e \) is the Ground Flash Density (GFD) (flashes/km²/yr);
- \( \eta \) is the arc rate;
- \( f(I) \) is the Lightning current amplitude probability density function.

Extend the two-dimensional EGM in space, that is, consider the protective arc and exposed arc corresponding to each point on the line, and finally form the protective arc and exposed arc in the entire span. Therefore, consider the entire span in the calculation, the parameters at different positions make the calculation results more accurate [6-9].

As shown in Fig.2, under any complex terrain and suspension mode, the sag corresponding to each point on the wire can be obtained by the catenary equation, and then according to the geometric method, the height of any point M on the wire can be obtained from the ground. The formula is as follows:

\[
H_{MC} = H_N + H_C - f_{MC} - l_M \times \tan \alpha - H_{ML}
\]  

(5)

where

- \( H_N \) is the altitude of the \( T_N \) tower;
- \( H_C \) is the distance between the tower conductor suspension point and the ground;
- \( f_{MC} \) is the sag of the wire at point M;
- \( l_M \) is the Distance from point M to the \( T_N \) tower;
- \( H_{ML} \) is the ground altitude corresponding to point M;
- \( \alpha \) is the height difference between the \( T_N \) tower and \( T_{N-1} \) tower.

![Fig.2 Schematic diagram for calculating the height of conductors and lightning line to the ground](image)

The formula for calculating the sag at any point on the line is as follows:

\[
f_s = \frac{g}{2\sigma \cos \alpha} x(l - x)
\]  

(6)

where

- \( g \) is the value of the load per unit length of the wire or ground wire converted to the unit area;
- \( \sigma \) is the internal force per unit area at a certain point of the section under investigation.
3. Calculation and Analysis of SFFOR of Collection Lines in Wind Farm

3.1. Calculation and Analysis of SFFOR of Collection Lines in Mountainous Wind Farms

Taking a wind farm as an example, combined with the weather station data in the vicinity of the wind farm, the area is a Class III meteorological area with an average annual thunderstorm day of 70 days. The altitude of the collection line of the wind farm is between 3400m-3600m. Considering that the air gap discharge follows the Paschen's law as the altitude increases, the atmospheric pressure decreases, the air density decreases, and the discharge voltage of the external insulation also decreases. Therefore, in the calculations in this article, the flashover voltage at both ends of the insulator is corrected, using "GB311.1-2012 Insulation Coordination Part 1: Definitions, Principles and Rules" Appendix B Altitude Correction Factor: for equipment operating at altitudes higher than 1000m, the air gap discharge voltage correction coefficient is shown in the formula:

\[ K_a = e^{\frac{H - 1000}{8150}} \]  

(7)

where

\( H \) is the altitude, m; \( q \) is the altitude correction factor, and the lightning impulse voltage correction factor is 1.0.

The research object of this paper is the I-circuit collection line of the wind farm. This collection line sends the electric energy generated by 17 wind turbines to the booster station in a series connection and confluence method. The double lightning protection line overhead line in the current collection line is 3.5km and there are 18 towers, numbered N1-N18. Fig.3 (a) shows the main tower structure of the collection line, and Table 1 shows the related parameters of the tower.

Table 1 Tower types and parameters

| Tower type   | Tower number | Calling height (m) | Height of wire to ground (m) | Wire protection angle (°) |
|--------------|--------------|--------------------|-----------------------------|--------------------------|
| JY142-15     | N1-N6        | 15                 | 19.5                        | 14.2                     | 14.2                     | 32.5                     | 17.7                     | 17.7                     |
| JY142-12     | N7-N9        | 12                 | 16.5                        | 11.2                     | 11.2                     | 35.0                     | 18.2                     | 18.2                     |
| NY142-18     | N10-N12      | 18                 | 22.5                        | 17.2                     | 17.2                     | 36.9                     | 15.3                     | 15.3                     |
| ZB152-24     | N13-N15      | 24                 | 23.2                        | 23.2                     | 23.2                     | 24.5                     | 0                        | 24.5                     |
| ZB142-18     | N16-N18      | 18                 | 17.2                        | 17.2                     | 17.2                     | 24.5                     | 0                        | 24.5                     |

(a) Schematic diagram of tower structure  
(b) Tower segment diagram line  
Fig.3 Schematic diagram of the main tower structure and section of the collection line
In the range of 3400m-3600m above sea level, the schematic diagram of the tower structure along the terrain of the current collecting line is shown in Fig.3 (b); according to the three-dimensional EGM method, the SFFOR of the collection line is calculated by considering the altitude correction coefficient and terrain factors, as shown in Fig.4 (a).

It can be seen from the Fig.4 (a) that between the N1-N5 towers, the SFFOR near each base tower is very close, and varies with the altitude; near the N6 tower, the SFFOR of the collection line changes significantly. It is mainly affected by the terrain on both sides of the N6 tower. The two sides of the N6 tower are valley terrain. The heights of the conductors on both sides to the ground are 24.72m and 25.08m respectively. Therefore, the SFFOR near the tower is the highest. For the N7 tower, although the conductors on both sides have 25.08m and 32.95m to the ground, its altitude is not as high as that of the N6 tower, and the structure of the N7-N8 tower is 12m higher than that of the N6 tower. The height is 3m, therefore, the SFFOR near the N7 tower is lower than that of the N6 tower.

In order to highlight the influence of mountainous terrain on the SFFOR of the current collection line, while maintaining the same parameters such as thunderstorm days, line layout, and tower structure, calculate the SFFOR of the current collection line at various intervals when the current collection line is erected on the plain terrain. The comparison diagram of the changed situation is shown in the Fig.4 (b).

It can be seen from the Fig.4 (b) that the SFFOR of the collection line under mountainous terrain is significantly higher than that of the plain area. From the calculation results, the SFFOR of the collection line under mountainous terrain is 0.487 times/100km/year. The SFFOR of the lower collection line is 0.167 times/100km/year, that is, the mountainous terrain is 2.9 times that of the plain terrain. In mountainous terrain, the power collection line has two ranges, that is, the seventh and the ninth range. The SFFOR is higher than 1.5 times/100km/year. The reason for this result is mainly due to the valley terrain in these two ranges, the larger the inclination of the ground and the short range, which leads to the highest SFFOR in these two ranges. Therefore, the mountainous terrain factors have a very important influence on the tripping rate of the current collection line by shielding. In the mountain area, the current collection line is more prone to tripping accidents caused by lightning shielding. However, the altitude of the two gears is not the altitude of the highest point of the collection line. Therefore, the SFFOR of the collection line does not show a positive correlation with the altitude, that is, the SFFOR does not increase with altitude.
3.2. Analysis of the SFFOR within the Span of Collection Line

In order to deeply study the influence of the terrain within the span on the SFFOR of the line, the N10-N12 tower of the double lightning line collection line is selected as an example, as shown in Fig. 5. In Fig.5(a), the black solid line represents the terrain change, the red and blue solid lines represent the lightning protection line and the wire respectively; the black curve in Fig.5(b) represents the SFFOR follow the span, and the red dotted line represents the average value of the SFFOR of the gear, and the average value is 0.657 times/100km/year. First of all, from the perspective of terrain, N10 to N11 are valley terrain, with a span of 386m long. In this span, the SFFOR near N10 and N11 are 0.7942 times/100km/year and 0.6584 times/100km/year respectively. The point with the largest shielding trip rate is 217m away from the N10 pole tower, and the value at this point is 1.2089 times/100km/year. Within this span, the reason for such changes in the SFFOR is that the lines near the tower are affected by the tip of the tower and are more susceptible to lightning strikes. The farther away from the tower, the probability of lightning strikes is relatively low. As it reaches the bottom of the valley terrain, the height of the wire to the ground continues to increase, and the shielding effect of the earth on the wire continues to weaken, resulting in the highest SFFOR in the middle of the valley. In the N11-N12 range, the terrain is uphill, and the span is 154m long. The SFFOR near the N12 pole tower is 0.7177 times/100km/year. Since this span is an uphill terrain, starting from the N11 tower, the height of the wire to the ground first drops and then rises, so the shielding effect of the earth on the wire is first increased and then decreased, which leads to the change in the SFFOR of this segment is first reduced and then increased.

In summary, the terrain within the span of the collector line has a very important influence on the SFFOR of the line. In the valley terrain, the height of the wire to the ground continues to increase, and the shielding effect of the earth on the wire continues to weaken, resulting in the position with the highest shielding trip rate in the middle of the valley. Therefore, in terms of SFFOR protection, the tower should be taken as the center, and the terrain on both sides of the tower should be considered to determine different lightning protection measures to effectively improve the lightning protection level of the collection line.

4. Conclusion

The following conclusions can be drawn from the above calculation and analysis of the SFFOR of wind farm collection lines:

(1) When the thunderstorm day, the arrangement of the collection line and the structure of the tower are the same, the SFFOR of the collection line of the wind farm in mountainous terrain is 0.487 times/100 km/year, and the plain terrain is 0.167 times/100 km/year, that is, the mountainous area is 2.9 times of plain terrain.
(2) Within the range of N10-N12 towers, the average SFFOR of the collection line is as high as 0.657 times/100kmꞏyear, and the SFFOR of the middle part of the valley in the N10-N11 range is close to 1.2 times/100kmꞏyear. Therefore, the terrain within the span of the collector line has a very important influence on the SFFOR of the line. In terms of SFFOR protection, the tower should be the center and the terrain on both sides of the tower should be considered to determine different lightning protection measures.

(3) It is recommended that in the initial design of the collection line of mountain wind farms, the use of double lightning protection lines with small protection angles should be considered, or after the line is put into operation, lightning arresters should be installed on the poles that are prone to flashover according to the terrain within the span to meet the design requirements of line lightning protection.

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