Simulation Study on Failure Mechanism of Composite Insulator Flashover Caused by Foreign Matter

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Abstract: Many typical non-lightning failures of transmission lines are caused by foreign matter, such as bird streamer, floating objects, branches and so on. In this paper, 110kV composite insulators are taken as the research object. First, the mechanism of flashover caused by foreign matter is analysed theoretically, and then a three-dimensional model of composite insulators is built by using the Maxwell simulation software. Electric field and potential changes of the composite insulator in the presence of different foreign matter are studied, and the flashover mechanism and related influencing factors are analysed. Based on this, through a large number of simulation calculations, the area of 110kV composite insulator caused by foreign matter flashover is finally given, which provides guidance for the typical non-lightning fault of 110kV line protection.

1 Introduction
Faults of transmission line includes lightning strike and non-lightning strike faults [1]. For some typical non-lightning faults, such as external breakage, tree flashover and bird damage (including bird's streamer flashover, bird's nest material short circuit and bird body impact, etc.) are all due to foreign matter near insulators, part or even all bridging high and low pressure air gap, resulting in flashover, which is abbreviated as foreign matter fault in this paper [2-4]. This type of fault occurs mostly in 110kV–220kV voltage grade transmission lines [3]. Because of longer air gap of insulators in 500kV and above lines, it is difficult to form a long enough foreign matter to make the flashover happen [4-6].

In paper [7], the mechanism of flashover caused by bird streamer is analyzed and the influencing factors of discharge are given. In paper [8], gap breakdown test of 220kV glass insulator string was carried out when bird's nest material fell down the gap next to the insulator, and gap breakdown characteristics of several different length bird nest materials were analyzed.

At present, foreign matter faults are mainly studied through experiments [9-10]. Because the approaching of foreign matter to insulator is dynamic, it is difficult to accurately analyze the specific influence of the length of foreign matter and space position on the discharge, and the change trend of the space electric field and potential is not clear [11-12]. In this paper, 110 kV composite insulator is taken as the research object. First, the mechanism of foreign matter fault is given by theoretical analysis, and then a three-dimensional simulation model is built by the Maxwell electromagnetic field analysis software, calculating the air gap electric field and potential related data with different length foreign matter and foreign matter in different space positions. Finally, the critical flashover area of foreign matter fault of the 110kV line is given, which provides a certain theoretical guidance for the transmission line to prevent the foreign matter fault.
2 Theoretical analysis
When foreign matter approaches insulator, it may part or even all bridge high and low pressure end air gap. The process of foreign matter approaching insulator is mainly contains the following cases: 1, foreign matter is long enough, such as long string bird streamer, which length can be more than 2m. In the process of its falling, its end part keeps connecting to the tower cross arm, and the front part is gradually close to the high voltage end until discharge occurs. 2, the length of foreign matter is not long enough, for example, part of bird's droppings, branches, bird's nest materials, and so on. During the falling of such foreign matter, flashover may occur at a specific moment when breakdown of both the gap between cross arm and end part of foreign matter and the gap between high voltage conductor and front part of foreign matter occurs. The two gaps are abbreviated to the upper gap and lower gap, respectively. 3, foreign matter approaches from the side of the insulator, which is similar to case 2. The schematic diagram of the above cases is shown in Figure 1.

![Figure 1. Sketch map of foreign matter approaching](image)

Foreign matter is in motion in the process of gap breakdown, however, because breakdown time is very short, foreign matter can be considered to remain stationary in the process of breakdown. In this paper, static conductor is used to simulate foreign matter.

The air gap between the end of foreign matter and fittings is a very uneven field when the gap spacing is less than 1m, similar to a typical rod-to-plate gap and rod-to-rod gap, with an average breakdown field strength of about 4 kV/cm. In this paper, 4kV is used as the critical breakdown field strength. If mean field strength of the gap reaches 4kV/cm, it is considered that the gap is broken, otherwise it will not break down.

For case 2 and case 3, the suspension potential $U_0$ of the foreign matter is calculated firstly, and then the average field strength of the two air gaps are calculated according to equation (1):

$$E_1 = \frac{U_0}{d_1}$$

$$E_2 = \frac{U_1 - U_0}{d_2}$$

(1)

In formula (1), $E_1$ and $E_2$ are electric field intensity of the upper gap and the lower gap, respectively. $d_1$ and $d_2$ are gap spacing of the upper gap and the lower gap, respectively. $U_1$ is the effective value of the phase voltage of the transmission line. The two gap breakdown is not strictly occurring at the same time. When one of the air gaps breaks down, the foreign matter potential jumps, causing voltage of the other gap mutating, the gap electric field need to be recalculated. For example, when the upper gap first breaks down, the foreign matter potential changes from suspension potential to zero at the breakdown instant, and the voltage of the lower gap mutate to $U_1$, and $E_2 = U_1 / d_2$ can be obtained.
3 Establishment of simulation model
The simulation model includes tower crossbar, composite insulator, conductor, metal fittings, foreign matter and so on. The type of composite insulator is FXBW4-110.

3.1 Model of foreign matter
Common foreign materials on transmission lines mainly include iron wire, wet branches and high conductivity bird droppings. In order to facilitate the calculation, in this paper, long straight cylindrical rod is used to simulate foreign matter, and the two ends of the foreign matter are smoothed.

For case 2 and case 3 in Figure. 1, the foreign matter potential is a floating potential and cannot be directly solved. In finite element study, the virtual large dielectric constant method is often used to solve such problems. The suspended conductive foreign matter is simulated by a material with a large dielectric constant. In this study, the value is 9000.

3.2 Models of cross-arm, wire, fittings and other parts
The tower and the cross arm were simulated with a simple rectangular metal plate, and the size was 2 m * 60 cm * 20 cm. The 110kV wire type is LGJ-240, the radius is 10.8mm, and the wire is simulated with a cylinder with a radius of 11mm. The earth is simulated with metal plates of length, width and height of 6m*6m*10cm. In consideration of good electrical conductivity, materials of cross arm, wire, and fittings are set to aluminum. Main components in the model are shown in Figure. 2 below.

(a) Model of 110kV composite insulator  (b) Model of foreign matter

Figure 2. Three dimensional simulation model of main parts

The applied voltage on the analog wire is the effective value of the operating phase voltage of the 110kV transmission line, that is, 110/1.732=63.5kV.

4 Simulation results

4.1 Simulation results of case 1
The spatial electric field distribution in two cases with or without foreign matter is shown in Figure. 3 below.

Figure 3. The influence of foreign matter in the spatial electric field

When foreign matter falls, its front end approaches the high pressure end continuously. When the air gap reaches the average breakdown field strength, the gap breaks down. Because the potential of the foreign matter is always 0, the average field strength of the gap can be calculated by dividing the conductor voltage by the gap distance. In order to analyze the change of electric field in the process of foreign matter falling, the relation between the field intensity at the front end of foreign matter and the falling distance of foreign matter was calculated.
Figure 4. The Relationship between the field strength of a foreign matter and its drop distance

As can be seen from the curve of Figure 4 above, with the falling of foreign bodies, the maximum field strength in front of the foreign matter becomes larger and larger, which indicates that the longer the foreign matter is, the easier the flashover occurs.

4.2 Simulation results of case 2

Taking a 70 cm long foreign matter falling from 18 cm away from the insulator axis as an example, the upper gap is 24.2 cm and the lower gap is 11 cm. The result of the calculation is shown in Figure 5.

Figure 5. Distribution of electric field and potential around the insulator in the presence of foreign matter

When foreign matter exists, the air gap of the insulator has obvious distortion, and the distortion near the foreign matter is more obvious. The spatial electric field and potential distribution at different positions are analyzed when the distance d between the foreign matter and the insulator axis changes. Take d=150, 180, 220 and 260 mm respectively, and the electric field and potential distribution are shown in Figure 6.

Figure 6. Electric field distribution and potential distribution when foreign matter exists

In Figure 6, d150N means d=150mm, and d is the distance between the foreign matter and the insulator axis. Y and N indicate the presence of foreign matter, of which Y indicates foreign matter, and N means no foreign matter. It can be seen from Figure 6 that the potential gradient changes significantly when foreign matter is present. Besides, from the trend of the curve, the potential change in the same height region as the foreign matter is relatively slow, and the potential gradient outside the
height of the foreign matter changes faster. Where \( d=180\text{mm} \) is the position of the foreign matter, the foreign matter suspension potential is 27.6kV, and since the foreign matter itself is a conductor, it is equipotential, corresponding to the straight portion of the curve \( d180Y \). It can be seen from the electric field distribution diagram that the presence of foreign matter causes the spatial electric field to be distorted. The closer to the ends of the foreign matter, the greater the distortion of the electric field. In Figure 6(b), the field strength of \( d180Y \) upper and lower end gaps is 1.1kV/cm and 4.4kV/cm respectively. The lower gap is breakdown, and then the foreign matter potential is abrupt to 63.5kV, so that the upper end air gap field strength is changed from 1.1kV/cm to 3.1kV/cm, which is still lower than the critical breakdown field strength, so no flashover occurs.

When the length of foreign matter is 70 cm, no flashover occurs during the entire falling of the foreign matter. On this basis, the average field strength of the air gap when a 95cm long foreign matter falls from the same position is further analyzed. The results are shown in Figure 7 below:

![Figure 7](image_url)

**Figure 7.** The change tendency of the average field strength of the two air gap

It can be seen from Figure 7 that when the vertical distance \( s \) between the front end of the foreign matter and the high-end end fitting is between 5 and 15 cm, the average field strength of the two gaps exceeds 4 kV/cm, and flashover occurs. However, when \( s \) is 0 to 5 cm or 20 to 25 cm, although one of the gaps is broken, since the other gap is too long to be broken, it is difficult to cause flashover.

4.3 Simulation results of case 3

In order to simulate the process of foreign matter approaching from the side of the insulator, the vertical position and length of the foreign matter are kept unchanged, and only the distance \( d \) between the foreign matter and the insulator axis is changed, and the field strength of the two gaps are as shown in Figure 8:

![Figure 8](image_url)

**Figure 8.** The change tendency of the average field strength of the two gaps

As can be seen from the Figure 8, as \( d \) increases, the gap field strength decreases. Therefore, the closer the foreign matter is to the insulator, the easier it is to flash.

4.4 Critical flashover area

When foreign matter is long enough, it is calculated that the flashover region is in the range of \( d<34.1 \) cm, that is, when a foreign matter falls along the region within the range of \( d<34.1 \) cm, flashover occurs. When the length of the foreign matter decreases, flashover area decreases or it even fails to flash, so flashover area is related to the length of the foreign matter. In order to obtain the relationship between the critical flashover area and the length of foreign matter, a large number of simulation...
calculations were carried out.

Under a certain \( d \), select an initial length foreign matter, simulate the process of falling from the top to the bottom of such foreign matter, calculate the two air gaps’ field strength at different drop points, determine whether the gap is flashover, and if it does not flash, increase the length of the foreign matter, if flashover occurs at multiple locations during the falling of the foreign matter, reduce the length of foreign matter.

The above process is repeated until the gap is flashed where foreign matter is at a specific point with a certain length, and no flashover occurs at the remaining points, and the area at this time is the corresponding critical flashover area. The relationship between the foreign matter-insulator axis distance \( d \) and the critical foreign matter length \( L_k \) is as follows:

\[
\begin{align*}
\text{Figure 9. Relationship between the critical flashover area and the length of foreign matter} \\
\text{When } d > 16 \text{cm, } d \text{ increases with the increase of the length of foreign matter, indicating that the longer the foreign matter, the larger the area of the critical flashover area. In Figure. 9, when the foreign matter length is 93 cm, the critical flashover region is a region of } d < 18 \text{ cm.}
\end{align*}
\]

5 Conclusion
1) When foreign matter is approaching to the insulator string, foreign matter with good conductivity causes the gap electric field and the potential to be abrupt. When the gap average field strength exceeds the gap critical breakdown field strength, breakdown occurs. The longer the foreign matter is, and the closer the distance from the insulator is, the easier the flashover occurs.
2) For 110kV composite insulator, the shortest foreign matter length that causes insulator to flash is approximately 90cm. If the foreign matter is long enough, it is a flashover region within a distance of 34.1 cm from the axis of the insulator. In order to reduce the occurrence of flashover, measures should be taken to avoid long strings of foreign matter approaching the insulator.

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