Simulation Research on Electric Field Distribution of Insulator String in ULTRA High Voltage Transmission Line

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Abstract. Insulators are one of the important components of overhead transmission lines. Because of their excellent characteristics, insulators have obvious advantages in the selection of external insulation in UHV AC transmission projects. The potential distribution of insulator string is not even due to the shape characteristics of insulator string, the structure of metal tool, the low conductivity of silicon rubber material and the stray capacitance between insulator string and wire, iron tower and metal tool. When the surface field intensity of insulators and fittings exceeds the initial field intensity, corona discharge will occur, which will affect the electromagnetic environment and the operation characteristics of insulating materials. Therefore, it is of great significance to determine the potential distribution of insulator strings of UHV transmission lines for detecting low and zero value insulators, implementing voltage equalization measures effectively, and ensuring the safe and stable operation of transmission lines. Based on Ansys software of 500kv transmission line insulator string, this paper establishes a three-dimensional model, the method of using finite element numerical simulation respectively with no equalizing ring and equalizing ring in both cases the umbrella skirt on simulation, the distribution of electric field along the roots, and further studies the equalizing ring the effect of different parameters on the electric field distribution. Finally, an optimal solution is established.

1. Introduction

As the insulation support of overhead transmission line, insulator plays an important role in EHV transmission project. Its performance directly affects the safe operation of the whole line. However, due to the very high voltage level, the length of insulator string increases sharply. Affected by the distributed capacitance of tower and high-voltage conductor, the electric field distortion of high-voltage conductor side and tower grounding side of insulator string is very serious. Usually, a grading ring is installed on the insulator string to increase the distributed capacitance between the insulator and the conductor, so as to effectively improve the voltage distribution of the insulator string. The grading ring can improve the potential distribution of the composite insulator and control the field strength in the high electric field area, prevent corona discharge, leakage trace and electric erosion, reduce audible noise, reduce the influence of ion current under DC field, and eliminate the degradation of non ceramic materials caused by corona [1]. Therefore, the optimal design of grading ring is an indispensable part in engineering application [2].

For decades, people have proposed various methods to measure the field strength distribution of insulator string, such as capacitance equivalent circuit method, analog charge method and mutually related field-circuit method [3, 4]. However, there is an inherent problem to be overcome in the measurement process, that is, the arrangement of measuring probe changes the electric field distribution.
of insulator string, which brings some systematic errors, and the test method has a long cycle and high cost, difficult to implement. In recent years, due to the great improvement of computer software and hardware, finite element method is widely used to solve electromagnetic field problems. It is not limited by environment and conditions, and can change the size and position of the calculation model at will, with good flexibility. The difficulty of optimizing the design of pressure equalizing ring is greatly simplified [5, 6, 7, 8].

In this paper, ANSYS finite element simulation software is used to simulate and analyze the potential and electric field without and with voltage equalizing ring, and further study the influence of various parameters of voltage equalizing ring on the electric field intensity distribution with voltage equalizing ring. It provides a good theoretical basis for installing grading ring on UHV transmission line in engineering.

2. The establishment of 3-D model
According to the actual situation of 500kV AC transmission line in China, a three-dimensional model of 500kV AC tower insulator string is established. The main parameters of the model in the modeling process are shown in Table 1. The tower type is wine glass tower, and the influence of the hollow network structure of the tower on the model simulation results is ignored. The insulator on the cross arm adopts vertical type I suspension mode, and the model of 4-bundle conductor is LGJ400 / 35.

| Essential information                          | Main simulation parameters |
|-----------------------------------------------|----------------------------|
| Length of insulator structure/cm             | 445                        |
| Mandrel diameter/cm                           | 2.4                        |
| Sheath thickness/cm                           | 0.6                        |
| Large and small umbrella diameter/cm         | 17, 8.4                    |
| Big umbrella spacing/cm                       | 8                          |
| Diameter of pressure equalizing ring/cm      | 40                         |
| Diameter of equalizing ring pipe/cm          | 6                          |
| Shielding depth/cm                            | 5                          |
| Height, width and thickness of tower/cm      | 3300, 400, 50              |
| Length, width and thickness of cross-arm/cm  | 1000, 400, 50              |
| Relative dielectric constant of FRP           | 7.2                        |
| Relative dielectric constant of silicone rubber | 4.3                      |

![Figure 1. Tower concept drawing [5].](image)

Although the electric field distribution of insulator string is not a strictly axisymmetric electric field, from the perspective of Engineering approximation, this paper considers that its electric field distribution is axisymmetric to the tower, so in the subsequent research, 1/2 tower model is taken for Simulation Research (as shown in Figure 1).
At the same time, some parameters of the model are also appropriately simplified during the research process:

1. In the process of modeling, the influence of tower on the electric field distribution of insulator string cannot be ignored, but its shape can be appropriately simplified, and the tower and cross arm can be simplified into two cuboids, which are made of steel;

2. In the process of modeling, the influence of conductor and connecting fittings on the electric field distribution of insulator string can not be ignored, but the appropriate length can be selected to establish the three-phase conductor model. In this paper, the length of conductor is 400cm, and the material of conductor and connecting fittings is aluminum;

3. In the process of modeling, it is generally considered that the phase to phase distance of three-phase AC is large, and the grounding tower has a certain shielding effect on the phase to phase electric field, so the phase to phase influence can be ignored, and only the simplified model of medium phase V-string can be established;

4. The size of the umbrella skirt on the protective sleeve and insulator string is made of silicone rubber, and the insulator core rod in the protection is made of glass fiber reinforced plastic;

5. Move the boundary at infinity to an appropriate distance close to the insulator, that is, replace the infinity boundary with a finite boundary. This treatment will enhance the electric field near the insulator, but because the overall size of the composite insulator is very small and the power line is very sparse not far away, the error to the calculation result is also small.

Finally, the excitation and boundary conditions are added to the established 1/2 tower simulation model: during the simulation, the lower end of the sub is connected with hardware and wires to add high-voltage excitation: \( U_0 = \frac{500}{\sqrt{3}} \times \sqrt{2} \times 1.1 \); add 0 excitation to the upper side of tower, cross arm, insulator and the outer surface of air domain.

The final ANSYS modeling results are shown in Figure 2 and Figure 3 below:
3. Analysis of simulation results

3.1. Effect of pressure equalizing ring with or without on electric field and potential distribution

The 500kV AC-tower-insulator string 3D model established above can analyze the electric field intensity distribution along the connection between the root of the umbrella skirt and the protective sleeve (Figure 4):

![Figure 4. Field intensity distribution along the root of umbrella skirt without pressure equalizing ring.](image)

As can be seen from the image, the electric field distribution along the root of the umbrella skirt is not uniform when there is no pressure equalizing ring, and the electric field intensity and potential reach the maximum at the point close to the connection point of the fittings and protective sleeve. Due to its shape characteristics, metal structure and low conductivity of silicone rubber material, the potential distribution of insulators attenuates rapidly from the high voltage end. Such potential distribution generates a high electric field at the adjacent high voltage end and the ground end. If the electric field intensity on the insulator surface exceeds the corona starting field, a corona discharge will occur. Obviously, in the absence of voltage equalizing ring, the electric field intensity on the high voltage side of insulator string far exceeds the corona field intensity.

Firstly, it is considered to install a pressure equalizing ring at the high voltage end of the insulator string on the basis of the above simulation model. The tube radius of the pressure equalizing ring is R=6cm, the ring radius is R=40cm and the shielding depth is D=5cm, as shown in Figure 5.

![Figure 5. Partial enlargement of the model after adding pressure equalizing ring.](image)

The simulation results show that the electric field intensity along the root of the umbrella skirt is significantly inhibited by the installation of a pressure equalizing ring at the high voltage end, namely at the bottom of the insulator string. At this time, the electric field intensity of the insulator string reaches
its maximum value at the distance of about 40cm (39.58cm) from the connection between the protective sleeve and the harness.

Figure 6. Field intensity distribution along the root of umbrella skirt with pressure equalizing ring.

After the voltage equalizing ring is installed at the high voltage end of the insulator string, the electric field intensity of the high voltage side along the root of the umbrella skirt changes obviously (as is shown in Figure 6), but the position where the maximum field intensity appears is almost unchanged. Meanwhile, the electric field intensity of the low voltage side does not change significantly. The potential distribution along the line has no significant change. Therefore, we focus on the influence of several different parameters of the pressure equalizing ring on the distribution of electric field intensity.

3.2. Effect of shielding depth on electric field intensity

The installation of pressure equalizing rings with different shielding depths is studied. This paper keeps the diameter of the pressure equalizing ring D=40cm and the diameter of the pressure equalizing ring D=6cm unchanged, then changes the shielding depth H to increase gradually from 5cm, and obtains the electric field intensity distribution curve along the root of the insulator string umbrella skirt when H =10cm, H =15cm, H =20cm and h=25cm respectively, and takes out the maximum group of electric field intensity of each group separately. Excel charts were drawn for comparison (Figure 7, Table 2). Excel charts were drawn for comparison (Figure 7, Table 2).

Table 2. Maximum electric field intensity at different shielding depths.

| Shielding depth/cm | Maximum electric field intensity/ (V/m) |
|--------------------|----------------------------------------|
| 5                  | 499086                                 |
| 10                 | 467158                                 |
| 15                 | 447526                                 |
| 20                 | 523203                                 |
| 25                 | 685307                                 |
Figure 7. Maximum electric field distribution diagram at root of umbrella skirt with different shielding depth.

As can be seen from Figure 8, with the increase of shielding depth, the maximum electric field intensity $E_{\text{max}}$ on the surface along the root of insulator string skirt decreases first and then increases. This is because the main position of electric field distortion of pressure sharing ring changes with the change of shielding depth. In addition, too deep shielding depth will lead to a substantial decrease in the lightning resistance level of insulators. Therefore, the field intensity distribution at the high voltage side of composite insulators can be improved by adjusting the shielding depth appropriately. The minimum value is 447526 V/cm when the shielding depth is 15 cm.

3.3. Effect of pressure equalizing ring diameter on electric field intensity
The pressure equalizing rings with different diameters were studied. This article keeps the shielding depth of pressure equalizing ring $h=15$ cm, the diameter of pressure equalizing ring tube $D=6$ cm, then changes the diameter of pressure equalizing ring from $30$ cm, takes a set of data every 10 cm, and gets $d=30$ cm, $D=40$ cm, $D=50$ cm, $D=60$ cm, $D=70$ cm, respectively. The electric field intensity distribution curve along the root of insulator string skirt when $D=80$ cm, and the maximum group of electric field intensity of each group was taken out separately to draw excel charts for comparison (Figure 8, Table 3).

Table 3. Maximum electric field intensity at root of umbrella skirt with different diameters of pressure equalizing ring.

| Diameter of pressure equalizing ring/cm | Maximum electric field intensity/(V/cm) |
|-----------------------------------------|----------------------------------------|
| 30                                      | 512564                                 |
| 40                                      | 447526                                 |
| 50                                      | 496325                                 |
| 60                                      | 709674                                 |
| 70                                      | 648777                                 |
| 80                                      | 635806                                 |
Figure 8. Distribution diagram of maximum electric field intensity at root of umbrella skirt with different pressure equalizing ring diameters.

It can be seen from Figure 8 that as the diameter of pressure equalizing ring increases, the maximum electric field intensity $E_{\text{max}}$ on the surface along the root of insulator string skirt decreases first and then increases. The minimum value is 447526 V/cm when the diameter of the pressure equalizing ring is 40 cm, so it is more appropriate when the diameter of the pressure equalizing ring is about 40 cm.

3.4. Effect of pressure-equalizing ring diameter on electric field intensity

The pressure equalizing rings with different diameters of pressure equalizing rings were studied. This article keeps the shielding depth of pressure equalizing ring $h=15$ cm and the diameter of pressure equalizing ring $D=40$ cm, then changes the diameter of pressure equalizing ring tube from 4 cm, takes a group of data every 1 cm, and obtain the electric field intensity distribution curve along the root of insulator string umbrella skirt when $D=4$ cm, $D=5$ cm, $D=6$ cm, $D=7$ cm, and $D=8$ cm, respectively. The maximum group of electric field intensity of each group was taken out separately and an Excel chart was drawn for comparison (Figure 9, Table 4).

| Loop diameter/cm | Maximum electric field intensity/ (V/cm) |
|------------------|-----------------------------------------|
| 4                | 539495                                  |
| 5                | 504197                                  |
| 6                | 447526                                  |
| 7                | 443634                                  |
| 8                | 448346                                  |

Figure 9. Distribution diagram of maximum electric field intensity at root of umbrella skirt with different pipe diameters.
It can be seen from Figure 9 that the maximum electric field intensity $E_{\text{max}}$ on the surface along the root of insulator string skirt decreases first and then increases with the increase of the diameter of pressure equalizing ring tube. The minimum value is 443634V/cm when the diameter of pressure equalizing ring pipe is 7cm, so it is more appropriate when the diameter of pressure equalizing ring pipe is about 7cm.

4. Conclusion

The distribution of electric field intensity at the root of umbrella skirt of 500kV UHV insulator string is approximately u-shaped, and the maximum electric field intensity of insulation part appears near the connection of high voltage end mandlet, protective sleeve and fittings. After installing a voltage equalizing ring at the high voltage end of insulator string, the electric field intensity at the root of insulator string parachute skirt can be greatly reduced. Meanwhile, changing the structural parameters of voltage equalizing ring will also affect the distribution of electric field intensity at the root of insulator string parachute skirt. The optimal solution can be obtained when the shielding depth is about 15cm, the diameter of pressure equalizing ring is about 40cm, and the diameter of pressure equalizing ring is 7-8cm. The conclusion can provide technical support for the design of new pressure equalizing ring of 500kV transmission line in the future.

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