Optimization for Grading Rings of High-speed Train Roof Post Insulator

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\textbf{ABSTRACT} In order to exercise control on the maximal intensity of electric field for the pantograph post insulators and fittings surface on high-speed trains, the finite element software COMSOL was applied to analyze the electric field distribution of post insulators in the presence and absence of the grading ring. According to the simulation results, the depth and degree of grading ring are the significant influencing factors in the distribution of electric field along the insulator surface and the surrounding air area. Based on these simulation results, the solid model was processed and the lightning impulse flashover voltage test was carried out. As indicated by the test results, the permissible lightning impulse voltage of 50\% negative polarity exhibited a linear relationship with the depth value, while 50\% of the permissible lightning impulse voltage generated with the addition of grading ring cover that was 70mm in depth satisfied the requirement of 170kV as specified in OV4 standard. Based on the results of simulation analysis and test, the parameters of the grading ring that can be applied in engineering works were identified in this paper, thus providing a reference for the adoption of the scheme to reduce the abnormal flashover frequency induced by the local high intensity electric field.

\textbf{INDEX TERMS} high-speed train, roof composite insulator, grading ring, lightning impulse voltage, electric field distribution

\section*{I. INTRODUCTION}

By December 2020, the overall mileage of high-speed railway networks in China reached 38,000 km. With the coverage of high speed railway networks in expansion, the operating environment of high-speed train has been made increasingly complex. Such exceptional meteorological conditions such as rain, snow, sand and high altitude can have an immediate impact on the stable operation of external insulation equipment fitted on the top of high-speed train [1-4].

The geometric model of a high-speed train was put into operation, as shown in Figure 1. The pantograph is purposed mainly to obtain the energy required for the operation of locomotive from the contact line through sliding contact. Supported by three insulators with silicone rubber and epoxy resin as its common sheath materials, the pantograph is intended to support the pantograph while enabling the electric insulation between high potential and vehicle body.

Due to the shape and fitting structure of post insulator used in pantograph on high-speed train, the pattern of potential distribution is uneven and the intensity of electric field is concentrated. A strong electric field tends to induce flashover fault, thus affecting the electromagnetic environment and insulating materials. The installation of grading ring device is regarded as the main solution to optimizing the distribution of local electric field, which is a common practice in the electric power system. In literature [5, 6], the 3D finite element model was adopted to calculate the distribution of surface electric field for 35kV and 1000kV composite insulators. With the random search method and particle
swarm optimization algorithm applied, the ring diameter and pipe diameter of the grading ring can be optimized, thus reducing the intensity of electric field at the sheath and end of mandrel. In literature [7-9] the calculation of surface potential and electric field distribution was based on the subdomain model method and the 3D finite element boundary element coupling method for the grading ring. Besides, an analysis was conducted regarding the impact made by diameter and cover depth of the grading ring on electric field distribution, with various factors taken into consideration to propose the optimal combination method. In literature [10-12], the insulator and thyristor in the converter valve were simplified into two-dimensional models. Based on the electric field calculation of two-dimensional and 3D examples, a calculation method was proposed to facilitate the surface electric field calculation of insulator for DC converter valve and the optimal design of voltage equalizing ring. In recent years, there have been plenty of studies conducted on the distribution of potential and electric field for insulator on the high-speed train roof. In literature [13-16] an analysis was carried out regarding the impact of shielding cover on the flashover characteristics of insulator of roof high voltage isolator, which led to a conclusion that the installation of shielding cover and shielding bolt can contribute to improving the distribution of local electric field and slowing down the aging of bolt thread end on the lower sheath material. Besides, the electrode structure of high voltage isolator was optimized. Cutting, sheet metal, welding and other processes were involved to process the fittings connected with insulators on both sides of the EMU roof pantograph frame. Due to the high intensity of electric field at the local tip formed in the process of cutting and welding, it was found out that corona discharge and flashover fault were most likely to occur in these places when the flashover characteristic test was carried out on the 1:1 high-speed train roof pantograph model [17-21]. The junction of core rod, fittings and sheath of silicone rubber composite insulator is considered the priority area to apply control on the range of intensity for electric field, which makes it necessary to analyze the distribution of intensity for electric field near the point of connection between the existing roof pantograph and silicone rubber composite insulator and to develop effective methods of optimization, which is significant to slowing down corner discharge and reducing the abnormal flashover fault frequency induced by local strong electric field [22, 23].

The structural height is merely 400mm for current insulators. The installation of grading ring will reduce the minimum distance between high and low-voltage electrodes, which may make the permissible lightning impulse flashover voltage fail to meet the requirements of contact system [24, 25]. Herein, a 3D model including pantograph frame was constructed to simulate the impact of structural parameters of shielding device on the distribution of intensity for local electric field with lightning impulse voltage excitation. Based on the simulation results, the optimal design of voltage equalizing shielding device was worked out, and the impact of its structural parameters on lightning impulse flashover voltage was characterized. Besides, the selection of voltage equalizing grading ring parameters appropriate for real-world operation was proposed.

II. SIMULATION MODELS
As shown in Figure 2, the plica tube shields the cable while protecting the outer sheath of the cable. Post insulators 2 and 3 are symmetrical with the symmetry line of the pantograph frame, one of which can be selected for analysis. In this paper, post insulator 2 was selected to conduct analysis.

![Diagram of EMU roof pantograph appearance.](image)

As shown in Figure 3. There are two main types of post insulators in operation. The sheath of insulator A is made of composite silicone rubber, which is widely used in engineering because of its excellent hydrophobic performance and anti-fouling performance. In this paper, the composite insulator A was selected for simulation and test. The sheath is numbered in ascending order from the high voltage side to the low voltage, with the insulator parameters listed in Table 1.
High voltage

Low voltage

(a) Composite insulator A

(b) Composite insulator B

FIGURE 3. Composite insulators in the net.

TABLE 1. Structural parameters of high-speed train roof composite insulator.

| Composite insulator type | Height (mm) | Rated voltage (kV) | Shed diameter (mm) | Leakage distance (mm) |
|--------------------------|-------------|--------------------|--------------------|----------------------|
| A                        | 400         | 27.5               | 190/170            | 1300                 |
| B                        | 400         | 27.5               | 400/280/245        | 1400                 |

With reference made to how power systems are defined, the grading ring is determined jointly by the parameter R (the radius of the grading ring), H (the cover depth of the grading ring) and θ (the degree of the grading ring).

The gasket between the existing high speed train roof insulator and the pantograph is 10mm in thickness, so that the thickness of grading ring can be set to 10mm.

The cover depth H of grading ring affects the electric field distribution on the surface of the composite insulator and its arc distance. Too much H will shorten the arc distance, resulting in a decrease in the impulse breakdown voltage; too small H will reduce the shielding effect of grading ring on the insulator, and the surface field strength will increase. Therefore, it is necessary to select an appropriate cover depth. As shown in Figure 3, the distance between the high-voltage side of composite insulator A and the 1st sheath is 72mm, and composite insulator B is 78mm. However, the cover depth H of grading ring cannot exceed the 1st sheath, so the maximum value of H shall be based on composite insulator A. Besides, the distance between the sheath of composite insulator A and the top of high-voltage fitting is 25mm, and composite insulator B is an integrated structure, the high-voltage fitting is completely wrapped by the sheath. The minimum depth of the grading ring is based on the principle that it completely covers the high-voltage electrode. In summary, when considering the cover depth of grading ring, the range of H should be between 25mm and 72mm. In the simulation, the minimum value of H is 30mm, and the maximum value is 70mm.

The determination of the parameter R needs to refer to the maximum length of the pantograph “ear” and the diameter of the 1st sheath of post insulator. Since the length is 210mm for the pantograph “ear” connected with the fitting at the high-voltage side of post insulator 1, its diameter is supposed to exceed this value for design of the grading ring. However, it is necessary to consider the size and insulation distance of the space around the post insulators in the design, leaving a certain amount of redundant space. Taking the effect of degree out of consideration, the minimum R of grading ring shall be 125mm for composite insulator A and 160mm for composite insulator B.

The traditional grading ring degree is 90°, considering the influence of high-speed air flow during train operation, the degree θ is first introduced into the design of the grading ring parameters. θ can not only affect the distribution of the local fluid flow, but also expand the shielding range. The expanded shielding range is mainly affected by H. As shown in formulas (1), (2), (3) and Figure 4, the thickness and bend of the grading ring need to be taken into account when calculating the total shielding radius. The diameter of the 1st sheath of composite insulator B is 280mm, when the grading ring with θ=90° and R=125mm is selected, the 1st sheath can’t be completely shielded. The shielding range increases with the increase of parameter θ, as shown in the table 2.

Taking the minimum cover depth H=30mm as an example, when θ=120°, the grading ring with radius R=125mm can meet the shielding requirements of composite insulator B; while θ=150°, the shielding range even increases to 373.4mm. Similarly, when H=30mm and R=145mm, the shielding range of the 135° grading ring reaches 366.7mm, and when H are 50mm and 70mm, the shielding range will be further expanded, but the diameter of 1st sheath of composite insulator A is only 190mm, so the shielding parameters of R=145mm and θ=150° are too large for it. Therefore, it is not recommended to use shielding parameters with θ greater than 135° and R greater than 135mm. In the simulation, the values of the degree θ are 90° (normal), 120° and 135°, and the values of the radius R are 125mm and 135mm. The total structural parameters of grading ring are listed in Table 3.
The assumptions made for the simulation are detailed as follows:

1. The impact of cable, plica tube, high voltage disconnector and other components on the strength distribution of 3D section line electric field along the surface and near the pantograph post insulator is negligible;
2. The surface of pantograph post insulator sheath and its grading ring is dry and clean;
3. The impact of altitude on electric field distribution is negligible.

The insulator models with different grading ring are shown in Figure 5.

**TABLE 2. Influence of θ on shield range.**

| Shield parameters | θ   | Increased shielding radius L₁ (mm) | Total shielding diameter (mm) |
|-------------------|-----|----------------------------------|------------------------------|
| R=125 H=30        | 90° | 0                                | 250                          |
|                   | 105°| 8                                | 275.6                        |
|                   | 120°| 17.3                             | 298.1                        |
|                   | 135°| 30.0                             | 326.7                        |
|                   | 150°| 51.9                             | 373.4                        |
|                   | 90° | 0                                | 290                          |
| R=145 H=30        | 105°| 8                                | 315.6                        |
|                   | 120°| 17.3                             | 344.1                        |
|                   | 135°| 30.0                             | 366.7                        |
|                   | 150°| 51.9                             | 413.4                        |

**TABLE 3. Grading ring structure parameters.**

| R (mm) | θ   | H (mm) |
|--------|-----|--------|
| 125    | 90° | 30     |
|        | 120°| 50     |
|        | 135°| 70     |
| 135    | 90° | 30     |
|        | 120°| 50     |
|        | 135°| 70     |

The 3D point and 3D section line are shown in Figure 6.

**FIGURE 5. Models diagram of post insulators.**

A. 3D point and 3D section line

The 3D point and 3D section line are shown in Figure 6.

B. Lightning impulse voltage excitation

Lightning strikes the railway catenary and invades the high-voltage system of the EMU along the pantograph. After the catenary is struck by lightning, an overvoltage with high amplitude and steepness will be generated in the power supply circuit of the EMU, which will seriously threaten the insulation safety of the electrical equipment in the car. In addition, the lightning impulse voltage is also a basic requirement for assessing whether the post insulator can be put into operation of the catenary network.

The front time of the standard lightning impulse voltage is 1.2μs and the half-wave peak time is 50μs, so that the double exponential wave form is expressed as follows:

\[ u(t) = u_0 k (e^{-\alpha t} - e^{-\beta t}) \]  (4)
In Equation (4), \( u_0 \) represents the peak lightning impulse voltage, which is 200 kV; \( k \) denotes the correction coefficient, which is 1.043; \( \alpha \) refers to the wave head attenuation coefficient and \( \beta \) stands for the wave tail attenuation coefficient, the value of which is \( 1.47 \times 10^4 \) and \( 2.08 \times 10^6 \), respectively\(^{[26]} \).

The pantograph model without grading ring is taken as an example in this paper to apply the excitation shown in Equation (1) on the high voltage side, so as to establish the pattern of changes in intensity of electric field over time at point A, as shown in Figure 7.

According to the simulation results, the variation in intensity of electric field at point A is consistent with the waveform of applied lightning impulse voltage excitation over time, with its maximum reached at about 2\( \mu \)s. For this reason, the subsequent simulation is focused only on analyzing the change to electric field intensity when the excitation voltage reaches its maximum.

**FIGURE 7.** Time-varying waveforms of 3D point electric field at standard lightning impulse voltage.

The first type of boundary condition (potential setting) is applied in this simulation. The size of the air field is over 5 times that of this model, while the electric potential at the low voltage side of insulator and the artificial boundary is set to zero. The relative dielectric constant of each material are shown in Table 4.

**TABLE 4.** Relative dielectric constant.

| Parameter          | Air     | Compound silicone rubber | Mandrel | Fitting |
|--------------------|---------|--------------------------|---------|---------|
| Dielectric constant| 1.0     | 3.5                      | 3.0     | \( 10^8 \) |

**III. SIMULATION RESULTS**

In the electrostatic field, its intensity is equal to the negative gradient of the potential. For analysis of the maximum variation in strength of electric field for the post insulator, the electrostatic field can be replaced by the transient electric field to facilitate calculation. Meanwhile, it is conducive to avoiding such problems as large computational workload and slow-paced calculation speed for the transient electric field. Based on the model shown in Figure 2, the 200kV voltage excitation is applied to the high voltage side to replace the transient electric field excited by lightning impulse voltage with a peak of 200kV.

As shown in Figure 8, before the fitting on the high voltage side of the post insulator is optimized, the areas with a high strength of electric field are concentrated at the connection point between the post insulator and the pantograph "ear" as well as in the root of the upper surface of sheath 1. In addition, there are holes present near the pantograph "ear", and the distortion to electric field occurs at the edge of those. After the installation of grading ring, what increases is limited to the strength of electric field at the interface between the grading ring edge and air, while there is a significant reduction in the extent to which electric field is unevenly distributed on the surface of 1\textsuperscript{st} sheath.

A grading ring is deployed on the upper surface of the high voltage side fittings, which makes the distribution of electric potential and electric field adjustable around the post insulator, while reducing the average intensity of the electric field near sheath 1 and the edge of the pantograph frame "ear". It offers protection to the sharp corners, solder joints and other tip parts left during the processing of the pantograph frame, and restricts them within the strength of corona electric field, thus reducing corona discharge.

**FIGURE 8.** Distribution of electric field of pantograph excited by lightning impulse voltage.

Since post insulators 2 and 3 are symmetrical with the axis, they were selected for analysis. As shown in Figure 9, there is a symmetry between front section line 2 and the rear one, as is between left section line 1 and the right one. Therefore, either of them can be selected for analysis. The rear section line 1 is shown as a dotted one because it is situated at the back of post insulator 1. In this paper, 6 section lines, including 3 section lines of post insulator 1 and 3 section lines of insulator 2, were selected to analyze the pattern of electric field distribution.
Figure 10 shows the electric field intensity distribution of 3D section lines for post insulators 1 and 2, with the maximum electric field strength of section line 1 right behind it. In comparison with the "ear" matched with post insulator 1 in Figure 2, it is connected with the pantograph through bending and welding for secure mechanical support. In this case, the field strength at the corner behind the "ear" is larger than at other positions. The pantograph "ear" matched with post insulator 2 can shield sharp corners and uniform electric field to a certain extent. The impact on left section line 2 is minimized by the pantograph "ear" due to the long distance from it among the three sections selected, which leads to the maximum level of electric field intensity. Compared with rear section line 1, the electric field intensity of left section line 2 is higher. As a result, post insulator 2 was selected to analyze the pattern of electric field distribution.

A. Influence of installing grading ring on electric field intensity distribution

With the model of pantograph frame matched with insulator and the single insulator model as the research object, a grading ring with \( R=135\,\text{mm} \), \( H=50\,\text{mm} \) and \( \theta=120^\circ \) was selected to simulate the sectional distribution of field intensity in the presence and absence of grading ring cover for insulator 2 of pantograph model and single insulator. As shown in Figure 11, the installation of grading ring is effective in significantly improving the uniformity of field strength distribution near sheath 1 on the high voltage side. As for the trend of changes in the distribution of electric field strength in section line for single insulator, it is basically consistent with the insulator matched with pantograph frame after the installation of grading ring. In order to analyze the impact of different grading ring parameters on the distribution of electric field strength for post insulator and reduce the shield effect of pantograph "ear", single insulator was selected for analysis and research.

As shown in Figure 12, the maximal level of electric field strength is reached at the corner of interface between the edge of pantograph post insulator fittings and the sheath, which is \( 4.56\times10^6\,\text{V/m} \). At this point, the curvature of the metal electrode is large. After the installation of grading ring, the strength of electric field declines sharply. Additionally, regardless of whatever kind of grading ring is installed, there

![Electric field distribution of post insulator with grading ring.](image)

(c) Comparison of maximum electric field intensities.

![Electric field distribution at different positions.](image)
is a significant reduction in the extent to which electric field strength is unevenly distributed on the surface of sheath 1 of post insulator. The existence of the grading ring reduces field strength near sheath 1 to 2.07×10^6 V/m, 54.6% which is lower than without grading ring.

![Cloud diagram of electric field intensity distribution of post insulator at peak of lightning impulse voltage.](image1)

Generally, it is stipulated in the project that the surface field strength of the insulator exceeds 0.45kV/mm, there is a possibility of corona discharge. As shown in Figure 13, applying a voltage excitation of 38.89kV (Rated voltage 27.5kV×√2) on post insulator, the maximum electric field strength on the surface of 1st sheath can reach 0.892kV/mm, which is far more than the corona initiation field strength, and it is easy to induce corona discharge. As shown in Table 5, after installing a 90° grading ring, the maximum electric field strength on the surface of 1st sheath is controlled within 0.375kV/mm, down 57.96%; When the 120° grading ring installed, the maximum electric field strength is 0.363kV/mm, which is 3.2% higher than that of 90° grading ring. The 135° grading ring has the most obvious effect on optimization, down 62.1%.

![Electric field cloud diagram of 1st sheath on rated voltage.](image2)

| Parameters       | Maximum surface field strength of 1st sheath (kV/mm) | Percentage reduction |
|------------------|-----------------------------------------------------|----------------------|
| Original         | 0.892                                               | 0                    |
| 90°R135H50       | 0.375                                               | 57.96%               |
| 120°R135H50      | 0.363                                               | 59.3%                |
| 135°R135H50      | 0.338                                               | 62.1%                |

B. **Influence of H on electric field intensity distribution**

Given the impact of grading ring degree on electric field, a 120° grading ring was selected for analyzing the impact of cover depth on the intensity of electric field along surface and 3D section line. As shown in Figure 14, the grading ring contributes to a significant reduction in the unevenness of electric field on the high voltage side and sheath 1 of the post insulator. Within the set simulation parameters, the larger the cover depth H, the better the optimization effect of the grading ring on the post insulator. Besides, the optimization effect is most desirable when the cover depth reaches 70mm. The intensity of electric field in the 3D section line plunges before the installation of grading ring. After the installation, however, the decrease in strength electric field on the 3D section line tends to be moderate. Moreover, the change in intensity of electric field on 3D section line stabilizes in general when the cover depth is 70mm.

Without optimization measures, the electric field intensity of 3D point A is 2.65×10^6 V/m, after the grading ring installed, the electric field intensity of 3D point exhibits a decreasing trend with the increase of cover depth, and the maximum electric field strength(H=30, R=125, θ=90°) after optimization is reduced by 1.24×10^6 V/m, down 53.2%, while the impact caused by degree and radius of the grading ring on the intensity of electric field for 3D points is insignificant. When the grading ring degree remains unchanged, the dot of grading ring with R = 125mm reaches above R = 135mm, as a result of which the optimization effect is less significant than when R = 135mm. Differently, the optimization effect of 135° grading ring is improved relative to 90° and 120° when the radius R of grading ring is constant. When H=70mm, the influence of R on electric field intensity is not obvious.
FIGURE 15. The influence of R on electric field strength.

D. Influence of θ on electric field intensity distribution
According to the analysis of depth and radius, the grading ring (H=70mm, R=135mm) with the most satisfactory optimization effect was selected for analysis. As shown in Figure 16, the 120° grading ring produces a better optimization effect on the top of the post insulator when the grading ring parameters H and R are fixed. In comparison, the 135° grading ring produces a less significant effect in path, due to the larger shielding range, its electric field strength even exceed 90° around the 1st sheath. Therefore, the 120° grading ring was selected for voltage equalizing.

FIGURE 14. The influence of H on electric field strength.

C. Influence of R on electric field intensity distribution
According to the results obtained from the depth analysis of the grading ring, the one with the best optimization effect produced at H=70mm was selected for analysis. As shown in Figure 15, there is a considerable decline in intensity of electric field at the top of the high voltage side of the post insulator after the installation of grading ring. With the depth H and the degree θ remaining unchanged, the change in parameter R of the grading ring has only marginal effects on the distribution of electric field on the path and the 3D section lines of the post insulator. As for the strength of electric field on the high voltage side, it is affected by H to a significant extent.
E. Influence of installing grading ring on distribution of fluid flow

The composite insulator on the roof of high-speed train is exposed to the air for a long time, and the impurity particles in the air absorb and deposit on the surface of the insulator to form a polluted layer, which may generate leakage current in humid environment even result in partial discharge on the insulator surface. The fluid flow near the insulator affects its contamination characteristics. The flow field characteristics near the insulator with different grading ring are shown in Figure 17. The airflow direction is from left to right and the speed is 80 m/s.

Without optimization measures, the eddy current is mainly concentrated on the leeward side of insulator. After the installation of grading ring, there is no obvious difference in the eddy current near the leeward side of 3#~9# sheaths except 1st and 2nd. Therefore, the installation of grading ring will not have much impact on the contamination characteristics of post insulator. With the increase of grading ring degree, the phenomenon of eddy current reflux above the 1st sheath of insulator is more obvious. When $\theta=135^\circ$, the reflux phenomenon is the most serious, which is more conducive to the adsorption and deposition of fouling particles.

IV. EXPERIMENTAL VERIFICATION

A. Test device

According to the simulation results, the grading ring as shown in Figure 15 was processed, and the lightning impulse flashover test was carried out using the wiring method as illustrated in Figure 18.

From Figure 19, it can be seen that the single stage output voltage is 150 kV for the impulse voltage generator, with a total of 3 levels and the maximum output voltage of 450kV. The lightning impulse voltage waveform is found compliant with the requirements of GB/T16927.1-2011, with a voltage divider ratio of 1000:1. During the test, the temperature was set to the range from 21 °C to 30°C, while the relative humidity was set to the range between 27% and 48%.

FIGURE 16. The influence of $\theta$ on electric field strength.

FIGURE 17. Characteristics of flow field near insulator.

FIGURE 18. Physical grading ring.
B. Test results

The existing high voltage electrical equipment of high-speed train adopted in China is designed to OV3 standard for matching the permissible test voltage applied in plain areas. The rated lightning impulse voltage of the external insulation equipment is 125kV for such high speed railways as Beijing-Guangzhou and Beijing-Shanghai high speed railways. However, the insulation of high-speed train equipment in high-altitude areas is supposed to reach up to the level set out in OV4 standard. Table 6 lists the permissible impulse voltage for those electrical devices operating at varying voltages and that for equipment with different rated voltages, as set out in the standard TB/T1333.1-2002 given the specific operating environment for locomotives. Therefore, the permissible lightning impulse voltage of electrical devices with a rated voltage of 25 kV should be no less than 170 kV.

According to the simulation results, the intensity of electric field at the high voltage side is affected by the parameter H to a significant extent. Figure 20 presents a scatter diagram for the permissible value of 50% lightning impulse voltage corresponding to the grading ring with different depth parameters.

As shown in Table 7 and Figure 20 that before the grading ring was installed, the permissible value of 50% negative lightning impulse voltage of the pantograph post insulator is -308.85kV, and the permissible voltage value is reduced when grading ring was added, but it can still meet OV4 standard, and the negative permissible value of 50% lightning impulse voltage decreases with the increase of the depth.

When the depth and radius of grading ring reach a certain level, the breakdown voltage of the 120° grading ring is invariably lower than that of 90°. Besides, the breakdown voltage of the grading ring with radius R=135mm falls below 125mm when H and θ of the grading ring reach a certain level. With the lightning impulse voltage of the post insulator without the grading ring cover as the criterion, the installation of a grading ring (H=30mm, θ=90° and R=125mm) will make the least significant difference to the permissible level of lightning impulse flashover, and the amplitude of the negative lightning breakdown voltage is reduced by 56.58kV, down 18.3%. After the installation of grading ring (H=70mm, θ=120° and R=135mm), however, the amplitude of the negative lightning breakdown voltage shows the most significant reduction relative to that without the grading ring cover, with the lightning impulse flashover voltage reduced by 93.12kV, down 30.15%.

With the test data listed in Table 5 fitted, the function relationship between the negative breakdown voltage U and the cover depth H as shown in Equation (5) can be determined.

\[
U = aH + b
\]

(5)
Where “a” represents the linear fitting coefficient and “b” is a constant. The corresponding “a” and “b” for different types of grading ring covers are shown in Table 8.

Table 8. The “a” & “b” values of different types of masks.

| θ  | R(mm) | a   | b   | R-square |
|----|-------|-----|-----|----------|
| 90°| 125   | 0.3918 | -263.1 | 0.9591 |
|    | 135   | 0.4124 | -262.3 | 0.9788 |
|    | 125   | 0.5305 | -259.1 | 0.9949 |
| 120°| 135   | 0.5220 | -252.2 | 0.9999 |

The R-square shown in Table 8 falls into the range of [0, 1]. The closer it is to 1, the more credible it is for the variable of the equation to explain U. The coefficients used to determine different types of grading ring in Table 6 all exceed 0.95. Therefore, this function relation is suitable for the calculation of other grading ring depths when the degree θ and radius R of the grading ring are constant.

Although the grading ring with H=70mm performs best in optimization and complies with the OV4 standard, the lower edge of the grading ring is close to sheath 1 of post insulator due to the excessively large cover depth. However, the structural height of the post insulator is merely 400mm. When the depth of cover is overly large, the air gap between the high voltage side and the roof will be reduced by the grading ring. Therefore, the cover depth of 70mm is considered too large for the insulators used in this study, which makes it unfit for application in engineering settings.

V. CONCLUSIONS

According to the above results, the following conclusion can be obtained:

1. The maximum electric field intensity on the surface of 1st sheath of post insulator can reach 0.892kV/mm without grading ring. After installing (H=50mm, R=135mm and θ=120°), the maximum electric field intensity reduced by 0.363kV/mm, down 59.3%.

2. Based on the results of simulation analysis and test obtained for permissible lightning impulse voltage, the recommended range of parameters for grading ring of composite insulator A is determined as follows: radius R is 125mm to 135mm, the cover depth H is 30mm to 50mm, and the degree is 120°. For composite insulator B, the parameters of R is 135mm, H is 30mm to 50mm and the degree is 120°. Although these parameters for insulator B may not be optimal, but they can meet its basic shielding requirements;

3. The installation of grading ring will affect the distribution of velocity and pressure in the local area on the top of post insulator, while the negative pressure area and eddy current change on the leeward side will affect the distribution of pollution on the sheath surface. In the future, it is necessary to conduct further research on the characteristics of distribution for flow field and pollution on the sheath surface.

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