Research on DC Corona Test of Typical Electrodes and Corona Limited Electric Field Magnitude for Valve Hall Fittings

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Abstract. In order to prevent the surface corona of valve hall fittings and obtain the corona limited electric field magnitude, the research designed dc corona test of spherical electrode and ring electrode with the different radius of curvature. The electrodes were used to imitate valve tower shield plate, grading ring, grading ball and grading shield for bushing. By the reason that the uneven electric field of irregular conductor can’t be calculated theoretically or measured accurately, the three-dimensional finite element model is used for simulating calculation. The variation of typical electrode corona inception electric field is analyzed and threshold value of corona inception electric field of valve hall fittings is acquired. With adequate modification, limited electric field magnitude for the project is proposed. The corona inception electric field magnitude of electrical equipment under the equivalent diameter of 200mm is 2000V·mm⁻¹, and that of electrical equipment with an equivalent diameter of more than 200 mm is 1200 V · mm⁻¹.

1. Introduction

Corona discharge is a kind of partial self-sustaining discharge of gas medium in uneven electric field, which is the common form of gas discharge. Corona discharge will bring many adverse effects on the safe and stable operation of the power grid. The effects of light, sound, heat and chemical reactions in the process of gas discharge will cause the energy loss. Pulse phenomenon will form high-frequency electromagnetic wave, causing interference. Corona discharge can also cause chemical reactions in the air, resulting in ozone, nitrogen oxide and other products, causing corrosion[1].

The corona discharge brings many hazards, so it is necessary to find out the influencing factors and prediction methods of corona discharge. In the last century, peek, an American engineer, conducted a large number of corona tests on two specially processed smooth equal diameter circular parallel wires, and obtained the corona field strength and the corona voltage, namely the famous peek formula[2,3]. According to the mechanism of air discharge, Khaled analyzed the relationship between the corona field strength of the conductor, air density and humidity, and concluded that with the increase of humidity, the corona field strength of the conductor will increase accordingly. When the relative air density is 1, the corona field strength of the conductor will increase by 0.6% for every 1g/m³ increase of the absolute humidity. In reference[4], the peek formula is modified, the roughness coefficient is introduced, and the value of roughness coefficient under different weather conditions is proposed, 1 for good weather and 0.8 for bad weather. In reference[5], the prediction of AC corona voltage of conductor under different atmospheric parameters and surface conditions is proposed. In reference[6],
the corona discharge characteristics and altitude correction method of line fittings in high altitude area are studied. The main research points of the above literature are discharge characteristics of outdoor conductor corona. Compared with outdoor conductor, the electromagnetic environment of the fittings in the valve hall is better under indoor, closed and micro positive pressure conditions, but the shape is complex, so it is impossible to calculate the corona field strength by peek formula or theory.

The shape and structure of different hardware in the valve hall are quite different. The curvature radius of the valve tower shield plate and some composite insulator grading rings are mostly mm, and the curvature radius of the grading shield ball is mostly m, that is to say, the corona field strength of different structures and shapes of the valve hall hardware may vary greatly. For this reason, the DC corona tests of the spherical and annular electrodes with different curvature radii are designed. The shielding plate and the grading ring of valve tower with small curvature radii in the valve hall are simulated with small ball and small ring, and the grading ball with large curvature radii in the valve hall and the grading cover of bushing are simulated with large ball to study their corona characteristics and control field strength respectively.

2. Corona test and analysis of small size electrode

2.1. Test scheme

The corona test of ball and ring was carried out in the high voltage hall. The maximum output voltage of the DC high-voltage generator used in the test is 300kV negative DC voltage. The output voltage is continuously adjustable with accuracy of 0.1kV. The generator is equipped with the shield ring at the output end and the control box. During the test, the hand-held meteorological instrument is used to record the real-time environmental parameters such as the air pressure, the temperature and humidity synchronously, and the ultraviolet imager is used to observe the corona discharge of the electrode [7]. The UV imaging technology can effectively observe corona discharge phenomenon, which has been widely used at home and abroad in recent years[8-10].

The electrodes used in the test are aluminum alloy ball electrodes and ring electrodes of different sizes and the surface states. The electrode shape and number are shown in Figure 1, and the electrode size parameters are shown in Table 1, in which the surface smoothness and cleanliness of the smooth ball electrodes are both high. The rough ball electrodes are solid aluminum alloy materials. In order to qualitatively study the influence of the different roughness on the corona characteristics, sand with different particle sizes are used on the surface respectively. The diameter of No. 8 ball is the same as that of No. 9 ball, and the surface is scored with the steel knife after being polished. The ring electrode is made of hollow aluminum alloy pipe by bending, and the joint adopts welding process, and has its own inner bracket.

![Figure 1](image_url) (a)Smooth ball electrodes; (b)Coarse ball electrodes; (c)Ring electrodes

The DC power supply, control box and UV imager for the test are shown in Figure 2. In the test, the electrode is supported on the top of the DC power supply by a certain length of hollow steel tube,
so as to reduce the shielding effect of the power supply with its own shielding ring on the test electrode and make the electrode more prone to corona. In order to prevent the error caused by the jitters of the imager during the observation process, the tripod is used to fix it in advance. Refer to relevant national standards[11] and industry standards, measure and record the corona starting voltage and extinction voltage of each electrode for many times.

2.2. Test results and analysis
Take ball 1 as an example, the corona ultraviolet image of the smooth ball electrode is shown in Figure 3, and the corona starting voltage and extinction voltage are shown in Table 1.

| Electrode number | 1   | 2   | 3   | 4   |
|------------------|-----|-----|-----|-----|
| Corona onset voltage | 138 | 182 | 214 | 262 |
| Extinction voltage    | 129 | 165 | 200 | 245 |

Table 1. Corona inception voltage and extinction voltage of smooth ball electrode

In the corona UV image, the position marked by the red circle is the corona point, and the small white light spot is the photon produced by the corona. It can be seen from the figure that the corona discharge of the smooth ball electrode occurs on the top of the ball. This is because the DC high voltage generator shield ring has the weakest influence on the corona discharge, so the surface electric field intensity is the highest, and the discharge conditions can be easily reached. At the same time, it can be seen that the number of UV photons in corona is small and the phenomenon is weak. In the experiment, different observers have different judgment bases on whether corona occurs. In this paper, the weak discharge which can last for more than 3 minutes is the judgment basis of corona. Take ball 8
as an example, the corona ultraviolet image of the rough ball electrode is shown in Figure 4, and the corona starting voltage and extinction voltage are shown in Table 2.

![Ultraviolet image of coarse ball electrodes’ corona](image1)

Table 2. Corona inception voltage and extinction voltage of rough ball electrode

| Electrode number | 6  | 7  | 8  | 9  |
|------------------|----|----|----|----|
| Corona onset voltage | 150 | 161 | 169 | 176 |
| Extinction voltage  | 135 | 140 | 128 | 156 |
| Environmental parameters | Altitude 400m. | Temperature 23.9°C. | Pressure 96.6kpa. | Relative humidity 63.0% |

Compared with the corona UV image of the smooth ball electrode, it can be seen that the corona discharge of the rough ball electrode is no longer limited to the top of the ball. Although the shielding ring has the weakest influence on this area, theoretically, the surface electric field strength is the highest, and it is most likely to discharge, but because the surface is no longer uniform, there are many randomly distributed local defects, resulting in electric field distortion points, so local corona occurs at these points first. If the voltage is increased further, the ball will transition from local corona to full corona. At the same time, it can be seen that the corona starting voltage of No.8 rough ball is lower than that of No.9 ball with the same diameter. Take ring 1 as an example, the corona UV image of the ring electrode is shown in Figure 5, and the corona starting voltage and extinction voltage are shown in Table 3.

![Ultraviolet image of ring electrodes’ corona](image2)

Table 3. Corona inception voltage and extinction voltage of ring electrode

| Electrode number | 1  | 2  | 3  | 4  |
|------------------|----|----|----|----|
| Corona onset voltage | 221 | 229 | 239 | 244 |
| Extinction voltage  | 189 | 208 | 200 | 222 |
| Environmental parameters | Altitude 400m. | Temperature 23.9°C. | Pressure 96.6kpa. | Relative humidity 63.0% |
The ring electrode has two curvature radius parameters, the outer diameter and the pipe diameter. The corona characteristic is complex. It is found that the discharge point of the ring electrode appears at the outer edge of the ring, and there may be corona discharge along the outer diameter of the ring. Under the same corona voltage, there are many discharge points. This is due to the highest field strength around the outer edge of the ring. Because the ring electrode is made of hollow aluminum tube, its surface state is not as good as the smooth ball electrode, and there are many local defects, which leads to corona discharge in many places.

The relationship between the corona starting voltage of the ball electrode and the diameter of the ball is shown in Figure 6. From this figure, it can be seen that the corona starting voltage of the ball electrode increases approximately linearly with the radius of the ball, that is to say, increasing the radius of curvature can significantly increase the corona starting voltage, which is also applicable to conductors of other shapes and structures. Compared with the polished No.9 ball and the scored No.8 ball, it can be seen that the surface state has great influence on the corona voltage.

In practical engineering, the corona voltage can be increased by increasing the radius of curvature of the hardware, and the surface state may be damaged during the transportation and installation, so the design of the hardware needs to keep the certain margin.

![Figure 6](image)

**Figure 6** Relationship between corona inception voltage and diameter of ball electrode

### 3. Corona test and analysis of large size ball electrode

#### 3.1. Test scheme

The corona test of large-scale ball electrode is carried out in the high-voltage hall. The DC voltage of the test is generated by the DC high-voltage generator with the rated maximum output voltage of 1800kV in the hall. Limited by the coupling capacitor and voltage divider of the test circuit, the actual output voltage is not more than 1000kV.

The electrode used in the experiment is a smooth aluminum alloy ball, and the manufacturing process of the ball is better. The sphere diameter is 500mm, 600mm, 700mm, 800mm, 900mm and 1000mm respectively, and it is connected with the tube bus with the diameter of 300mm by the way of terminal ball encapsulation. As shown in Figure 7, the electrode is arranged in the form of ball plate electrode, which is the aluminum alloy smooth ball for test, and the plate electrode is the grounding iron sheet laid on the ground.
The test procedure is similar to the small ball corona test. The positive and negative corona tests are carried out independently for each ball electrode with different diameters, and the corresponding test phenomena and data are recorded. Test and record the same sample for many times, and take the average value as the corona voltage of the electrode.

### 3.2. Test results and analysis

During the test, the environmental parameters are: altitude 95m, air pressure 100.1kpa, temperature 17.4 °C, relative humidity 49.3%. In the positive corona test, the corona starting voltage of 500mm diameter ball electrode is 650kV. The corona starting voltage of 600mm diameter ball electrode is 735kV. The corona starting voltage of 700mm diameter ball electrode is 830kV. The corona starting voltage of 800mm diameter ball electrode is 910kV. No corona discharge was observed at 900 mm and 1000 mm ball electrodes.

In the negative corona test, the corona starting voltage of 500mm diameter ball electrode is 570kV. The corona starting voltage of 600mm diameter ball electrode is 650kV. The corona starting voltage of 700mm diameter ball electrode is 735kV. Corona starting voltage of 800mm diameter ball electrode is 790kV. The corona starting voltage of 900mm diameter ball electrode is 850kV. The corona starting voltage of 1000mm diameter ball electrode is 880kV. Take 600mm ball electrode as an example, the UV image of positive and negative corona is shown in Figure 8.

The process of positive corona discharge is more intense, the number of photons is more, the corona is explosive, a lot of crackle can be heard on site, and the audible noise, pulse and radio interference produced by corona are relatively large. The corona of negative wire is relatively mild, the number of photons is small, and the audible noise is relatively small. According to the corona...
initiation voltage of the same diameter ball electrode, the corona initiation voltage of the negative electrode is about 100kV lower than that of the positive electrode, but the gap breakdown voltage is high. All of the above are typical manifestations of DC corona polarity effect of fittings, that is, the negative corona starting voltage is low, the breakdown voltage is high, the corona burst is moderate, the number of photons is small, the noise is low, and the positive polarity is just the opposite. This polarity effect is mainly caused by space charge: air ionization and corona discharge produce positive ions and electrons, the electron mass is small, the acceleration is large in the electric field, and it can obtain higher moving speed and rapid dispersion. The positive ion mass is large, the acceleration is small, the moving speed is slow, and it is not easy to obtain higher moving speed in a short time, so it is gathered in the corona area of the electrode. For the positive polarity, the space charge formed by the positive ions at the electrode head strengthens the external electric field and weakens the electric field in the corona area, making the corona not easy to occur and the streamer easy to develop. Under the negative polarity, the role of space charge is just the opposite, resulting in the above polarity effect[12].

The two corona tests were carried out in Xi'an and Beijing respectively. The altitude difference is about 300m, the temperature difference is about 6 ℃, and the absolute humidity is about 16g · M⁻³ and 8g · M⁻³ after conversion. The air density correction factors and humidity correction factors obtained by referring to the relevant national standards [12] are small, and the difference between them is not significant. Under the two experimental conditions, the arrangement of the ball electrode forms the isolated ball electrode electric field with partial shielding and the ball plate electrode electric field with the long gap, and the electric field forms are extremely uneven. Therefore, if the difference of meteorological conditions, altitude correction coefficient and electrode layout of the two tests are not considered temporarily, the corona voltage data of the smooth ball electrode obtained from the two tests can qualitatively obtain the corresponding relationship between the corona voltage of the smooth ball electrode and the diameter of the ball in the range of 33mm to 1000mm, as shown in Figure 9.

![Figure 9 Relationship between corona inception voltage and diameter of smooth ball electrode](image)

It can be seen from the figure that with the increase of the diameter of the ball, the corona initiation voltage also increases. When the diameter of the sphere is less than 600 mm, the slope of the curve remains unchanged. After that, the slope of the curve decreases, and the increasing speed of the corona voltage slows down. Its deep physical meaning is: with the increase of the diameter of the ball, the electric field non-uniformity coefficient of the extremely nonuniform electric field formed by the ball plate electrode gradually decreases, and electric field distortion effect of the ball electrode gradually weakens. This effect is more obvious when the diameter of the ball electrode is large, so the increase of corona electric pressure slows down. It can be predicted that as the diameter of the ball continues to increase, the growth rate of corona onset voltage will become more stable.
ball is large enough, the ball plate electrode with a 3M gap will gradually transition to the curved surface plate electrode (in extreme cases, it can be regarded as the plate plate electrode), and the gap electric field will gradually transition from the extremely uneven electric field to the slightly uneven piezoelectric field. At this time, the corona onset voltage of the ball electrode will be able to match that of the 3M gap Discharge voltage comparison.

4. Study on surface control field strength of valve hall hardware

4.1. Simulation analysis of electrode

Non-uniform electric field around the electrode studied in this paper can not be calculated analytically by the basic theory of electromagnetic field, so the finite element simulation method is needed. The finite element method is the numerical calculation method based on the variational principle and subdivision interpolation. Its theoretical model is suitable for all kinds of physical fields and physical processes described by the differential equations, as well as the time-varying field and nonlinear field complex physical fields such as fields and multi-media fields.

According to the actual layout of the experimental platform and the electrode size, the corresponding simulation model is established. In large-scale ball electrode test, the influence of other surrounding equipment on the test layout should be fully considered. The model diagram of each test is as follows:

According to the corona voltage measured in the corona test, the field intensity distribution is obtained. Take 56mm ball, No.2 Ring and 1000mm ball as examples, and the field strength distribution obtained by simulation calculation is shown as follows:
Figure.12 Simulation result of No.2 ring electrodes

Figure.13 The surface electric field distribution of 1000mm ball electrodes

It can be seen from the above figure that the maximum field strength on the surface of the small ball electrode appears on the top of the ball, the maximum field strength on the surface of the ring electrode appears on the upper side of the outer edge of the grading ring, and the maximum field strength on the surface of the large ball electrode appears near the ground aluminum plate at the bottom of the ball, which is basically consistent with the position of the corona ultraviolet photon observed in the test.

4.2. Electric field strength of corona initiation and control of hardware

When the structure and layout of the fittings are determined, the corona initiation voltage and control field strength are closely related to the current environmental parameters such as the temperature, humidity, air pressure, altitude, etc. The effect of air pressure and altitude is mainly reflected in air density, which essentially affects the average free path of electrons and the probability of collision and ionization. In general, as the altitude increases, the air pressure decreases, and the air density decreases. The three can be converted by referring to relevant standards.

Refer to the national standard, when the test environment temperature is 10℃~40 ℃, and the relative humidity is 20%~70%, the influence of temperature and humidity can be ignored, and only air density correction can be carried out. In addition, the standard also stipulates that for the case below 1000m altitude, altitude correction may not be carried out.

The two tests were carried out in Xi'an and Beijing respectively. The temperature, humidity, altitude correction and electrode layout difference of the two tests are not considered temporarily. According to the simulation results, the corresponding corona field strength of different types of electrodes under the corona voltage is shown in Table 4 and table 5:

According to the simulation results, the curve of the corona field strength of the smooth sphere electrode and the diameter of the sphere is made, as shown in Figure 14.
It can be seen from Figure 14 that with the increase of the diameter of the smooth ball electrode, the corona field strength shows a nonlinear downward trend: when the diameter of the ball is small, the corona field strength decreases rapidly. When the diameter of the ball is large, the corona field strength slows down. The turning point of the curve appears at the position where the critical diameter $d = 200\text{mm}$, and the corresponding field strength is about $2500\text{V} \cdot \text{mm}^{-1}$. At the same time, it can be seen that under the same electrode arrangement, the corona field strength of the positive electrode is about $275\text{V} \cdot \text{mm}^{-1}$ higher than that of the negative electrode. In addition, it can be seen that when the size of the sphere electrode is large, the corona field strength decreases slowly and changes approximately linearly. Therefore, a straight line with a smaller slope can be used for fitting in this region to approximately express the change relationship between the two.

| Electrode diameter/mm | 33   | 56   | 88   | 120  | 500  | 600  | 700  | 800  | 900  | 1000 |
|-----------------------|------|------|------|------|------|------|------|------|------|------|
| Corona field strength (negative polarity) | 4019 | 3690 | 3269 | 3128 | 1926 | 1917 | 1896 | 1828 | 1793 | 1760 |
| Corona field strength (positive polarity)  | 2197 | 2168 | 2141 | 2160 |      |      |      |      |      |      |

Table 5. Corona inception electric field of coarse ball and ring electrodes

| Electrode number | Ring | Ball |
|------------------|------|------|
| Corona field strength | 4050 | 4039 |
| Corona field strength | 3949 | 3865 |
| Corona field strength | 3829 | 3519 |
| Corona field strength | 3253 | 3388 |

5. Conclusion

In this paper, the DC corona test of typical ball and ring electrodes with different size parameters is designed, and the corona field strength of the fittings is studied in depth by combining the finite element simulation calculation. The fitting formula of the corona field strength of the smooth ball electrodes in a large diameter range is proposed, and the deep physical meaning of the formula is discussed. On this basis, the field strength correction problem is discussed, and the surface field strength control value of the valve chamber accessories table is proposed. Through the above research, the relevant conclusions are as follows:

1) DC hardware corona has obvious polarity effect, that is, the negative corona is relatively mild, the number of photons is small, the noise is small, it is easy to corona, it is difficult to breakdown, the positive polarity is just the opposite. When the radius of curvature of the fittings increases in a small range, the corona voltage increases approximately linearly, but in a larger radius, the corona voltage increases with saturation.
2) In the in-homogeneous electric field, the corona field strength of conductor decreases with the increase of curvature radius. When the diameter of smooth sphere electrode increases from 33mm to 1000mm, the corona field strength decreases from 4019V · mm⁻¹ to 1760V· mm⁻¹. When the diameter of the ball is small, the intensity of the corona field decreases rapidly. When the diameter of the ball is large, the intensity of the corona field decreases slowly. The turning point of the curve appears at the critical diameter of about 200 mm, corresponding to the field strength of 2500 V · mm⁻¹.

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