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*Original Paper*

# Optimal Design of Insulation of 3.6kV Vacuum Interrupter

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***Abstract***

*This paper compares and analyzes the insulation structure of the vacuum interrupter, focusing on the influence of the mechanical characteristics and the structure of the shield on the insulation, and establishes an electric field calculation model for the axisymmetric structure of the vacuum interrupter. Finally, the radius of the conductive rod and the thickness of the contact are compared and optimized, and then the thickness of the shield is compared and calculated, and then simulated and analyzed with ANSYS software to verify the optimization direction.*

***Keywords***

*vacuum interrupter, Insulation structure, electric field, magnetic field, Ansys msoftware*

## 1. Introduction

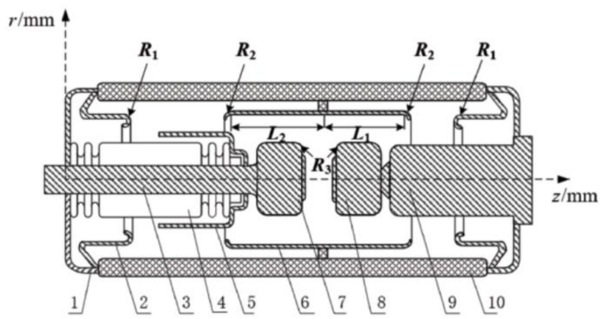
The circuit breaker is one of the most important control and protection equipment in the power system, and plays a vital role in the power system. The circuit breaker that uses vacuum as the insulation and arc extinguishing medium is called a vacuum circuit breaker, and the vacuum interrupter is one of the core structures that determine the breaking characteristics of the vacuum circuit breaker.

The vacuum range of the vacuum interrupter is $1.33 \times 10^{-5} \sim 1.33 \times 10^{-2} Pa$. It belongs to the high vacuum range, so the insulation strength between the contacts is very high. Its arcing time is short, the electrical life is relatively long, the contact opening distance and stroke are small, the operating energy is small, and the mechanical life is relatively long, so it is widely used in circuit breakers of 35 kV and below.

The static insulation level of the vacuum interrupter is the basis for improving the overall insulation reliability of the vacuum circuit breaker, and the optimization of the internal insulation structure of the vacuum interrupter is the main way to improve its static insulation level. Therefore, this article will try to optimize the internal structure of a 3.6kV vacuum interrupter to improve its insulation level.

## 2. Basic Structure of the Arc Extinguishing Chamber

The arc extinguishing principle of the vacuum interrupter is mainly to use the excellent characteristics of the vacuum medium to enable the vacuum circuit breaker to quickly extinguish the arc after disconnecting the circuit, so that the vacuum circuit breaker can be successfully broken. The close and open operation of the vacuum switch is accomplished by closing or separating a pair of opposite contacts in the vacuum interrupter chamber through the operating mechanism located outside the vacuum interrupter chamber. The vacuum interrupter is mainly composed of insulating shell, shielding cover, moving and static contacts, bellows and other parts. The main structure of the 3.6kV vacuum interrupter studied in this paper is shown in the Figure 1:




1-end cover;2-end shielding;cover 3-moving conductive rod;
4-corrugated pipe;5-corrugated pipe shielding cover
6-main shielding cover;7-moving contact;8-stationary contact
9-static conductive rod;10-insulating shell

**Figure 1. Physical Model of the Vacuum Interrupter**

## 3. Insulation Analysis of Interrupter

The key to the design of a high-voltage vacuum interrupter is the design of the electric field. One of the purposes of the optimal design of the electric field is to reduce the probability of breakdown, which is determined by the electric field on the electrode surface. Reasonable design of the size and structure of the internal parts of the vacuum interrupter can effectively improve its insulation performance. The main parts that affect the insulation performance of vacuum arc extinguishing include moving and static contacts, main shielding cover, end shielding cover and bellows shielding cover, etc. Reasonably modify the internal structure of the arc extinguishing chamber to reduce the concentration of electric field intensity and make the electric field inside the arc extinguishing chamber evenly distributed.

The maximum field strength in the vacuum interrupter decreases with the increase of the contact distance. Under the same contact radius, the larger the contact radius, the smaller the maximum field strength. According to the withstand voltage requirements of vacuum interrupters of different voltage levels, setting a voltage equalizing shield at a suitable position inside the interrupter can effectively improve its potential distribution.

*3.1 Influence of Mechanical Properties on Insulation*

The quality of the conductive rod and the moving contact affects the opening and closing mechanical characteristics of the vacuum circuit breaker. The change of mechanical parameters is also accompanied by the change of electrical performance. The change of the radius of the conductive rod and the change of the thickness of the contact determine the change of its corresponding quality. Since the ends of the contacts and the movable conductive rod are wrapped in the vacuum interrupter, it is necessary to first analyze the influence of the conductive rod and the contact on the electric field inside the interrupter.

The dynamic and static conductive rods are internally assembled with dynamic and static conductive rod cores. Because the energy required for breaking the vacuum interrupter is small, a transmission device with a simple mechanism can be selected. By assembling the structure of the dynamic and static conductive rod cores in the center of the dynamic and static conductive rods, the mechanical strength of the dynamic conductive rods is effectively improved. Under the same extrusion stress, the pole core can prevent the conductive pole structure of the fast mechanical switch from being thickly deformed due to mechanical impact. The density of the core material of the dynamic and static conductive rods is lower than that of copper, which reduces the mass of the dynamic conductive rod, thereby reducing the closing bounce and ensuring electrical performance.

The material of the contact directly affects the breaking capacity of the interrupter. The requirements for contact materials are: (1) Higher breaking capacity. In order to limit the development of the arc and to extinguish the arc faster, the selected material has high electrical conductivity, small thermal conductivity, large heat capacity, and low thermal electron emission capability. (2) Can withstand higher breakdown voltage. The higher the breakdown voltage of the gap dielectric, the higher the recovery strength of the dielectric, which is conducive to arc extinguishing. The contact should be made of materials that can match the dielectric strength. (3) High electrical corrosion resistance. Under the ablation of the arc, the less the contact metal evaporates, the better it is to maintain the insulation strength. (4) Resistance to fusion welding. (5) Low cut-off current value, hopefully below 2.5A. (6) Low gas content.

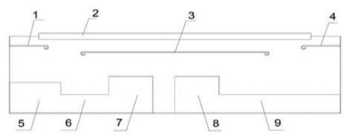
*3.2 Influence of Shield Structure on Insulation*

The contact gap is the space for breaking in the vacuum interrupter. The vicinity of the contact is the part where the arc is generated and extinguished, and the requirements for the surrounding materials and structures are relatively high. When the contacts break the current, a vacuum arc will be generated. Due to the excellent insulation performance of the high vacuum gap, the arc between the contacts is extinguished within a short distance inside the arc extinguishing chamber.

The potential changes between the moving and static contacts of the vacuum interrupter, and between the contacts and the shield are relatively significant. The distribution of the electric field inside the arc extinguishing chamber is not uniform. With the increase of the distance between the contact gap, the radius of the contact and the radius of curvature of the chamfer, the effective area of the contact surface will increase, while the maximum field strength inside the arc extinguishing chamber will decrease. Small, increasing the radius and length of the main shield can reduce the field strength at both ends of the shield. Installing multiple shielding covers in the vacuum interrupter can improve the internal electric field distribution.

## 4. Structural Optimization of the Arc Extinguishing Chamber

The structure of a 3.6kV vacuum interrupter is as follows:




1,4-end shielding cover;2-insulating shell;3-the main shielding cover;
5-corrugated pipe shielding cover;6-moving conductive;7-moving contact;
8-stationary contact;9-static conductive rod

**Figure 2. Simplified Model of 3.6kV Vacuum Interrupter**

According to the withstand voltage requirements of vacuum interrupters of different voltage levels, setting a voltage equalizing shield at a suitable position inside the interrupter can effectively improve its potential distribution. According to the axisymmetric structure characteristics of the vacuum interrupter, an electric field calculation model is established. According to the regulations of GB/T 11022-2011, the insulation capacity of 12 kV arc extinguishing chamber shall be considered according to the rated lightning impulse withstand voltage.

### *4.1 Preliminary Optimization of the Structure*

The maximum field strength in the vacuum interrupter decreases with the increase of the contact distance. Under the same contact radius, the larger the contact radius, the smaller the maximum field strength. In order to solve the problem of extremely uneven electric field distribution at the edge of the contact and large potential changes near the static conductive rod, a 1mm chamfer is set on the edge of the contact. After these two steps of preliminary optimization, the electric field and electric distribution are shown in the Figure 3.

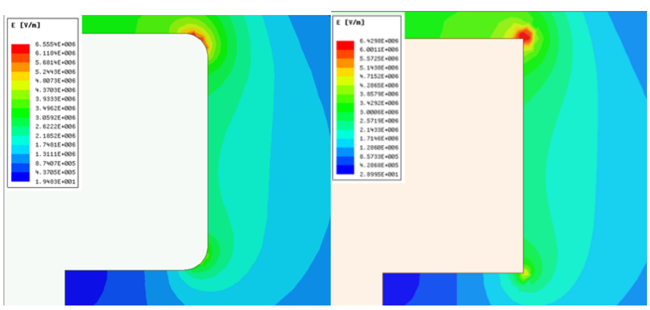


**Figure 3. Electric Field Distribution around Static Contacts**

In order to analyze the influence of the radius of the conductive rod on the potential and electric field distribution, control variables, and only change the radius of the conductive rod, the models were established separately, using the same material, excitation, solution domain and boundary condition settings. When the radius of the conductive rod is maintained at 6mm, the radius of the conductive rod is increased to 8mm, and the radius of the conductive rod is reduced to 4mm, the change of the radius of the conductive rod has little effect on the potential distribution inside the arc extinguishing chamber in the three cases.

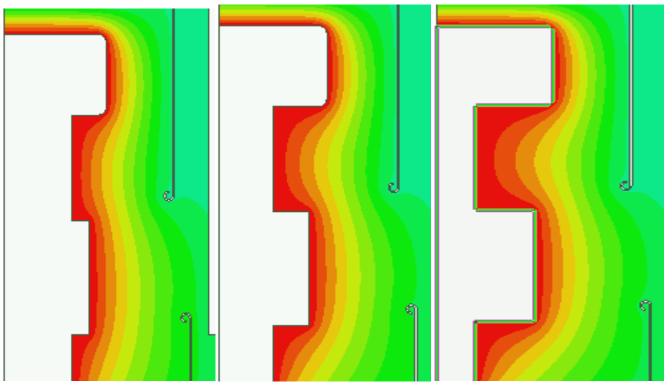


**Figure 4. Influence of Radius of Conductive Rod on Potential Distribution**

The breaking current of cylindrical contacts is related to the contact diameter. When the breaking current is small, the breaking current can be effectively increased with the increase of the contact diameter, but when it is close to 10kA, it tends to a saturated state. At this time, continuing to increase the contact diameter has no significant effect. Because the vacuum arc will produce a strong contraction phenomenon under a large current, it will be converted from a diffused vacuum arc to a concentrated vacuum arc, resulting in the failure of breaking. In the preliminary design of the size, it has been considered that the limit breaking current is 12.5kA, which is greater than 10kA, so the radius of the contact is no longer optimized.

The changes of electric field and potential were analyzed in three cases when the contact thickness was kept at 10mm, the contact thickness was increased to 12mm and the contact thickness was reduced to 8mm.

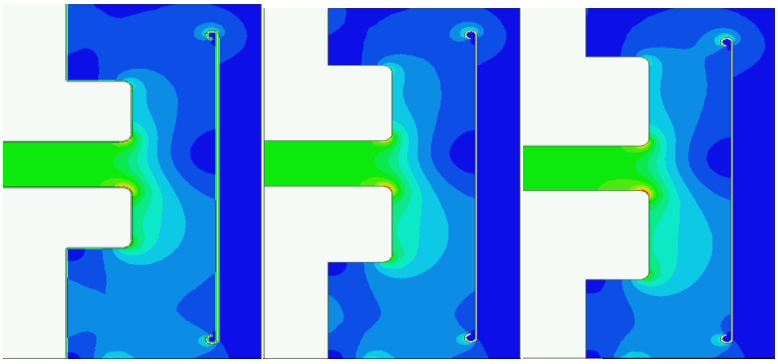


**Figure 5. Effect of Contact Thickness on Electric Field Distribution**

After increasing the thickness of the contact, because the inertia during the opening and closing process is greater, the erosion caused by the bouncing process is likely to increase the unevenness of the contact surface, and the maximum value of the field strength inside the arc extinguishing chamber rises sharply, which is not conducive to The internal insulation capacity of the arc extinguishing chamber is improved; after increasing the thickness of the contact, the distance between the back of the moving contact and the end of the floating shield is reduced, because the overall length of the arc extinguishing chamber is still suitable, and the field strength in the gap between the two is not obvious increase. It can be seen from Figure 5.5 that appropriately increasing the thickness of the contacts can make the electric field distribution inside the arc extinguishing chamber more uniform, so the thickness of the moving and static contacts is increased from 10mm to 12mm.

*4.2 Structure Optimization of the Shielding Cover*

The electric field at the top and bottom of the static contact in the first-step design of the electric field cloud diagram changes greatly, which is very easy to cause breakdown; and the voltage around the bottom of the static contact also changes greatly, which is also easy to cause breakdown. According to the withstand voltage requirements of vacuum interrupters of different voltage levels, setting a voltage equalizing shield at a suitable position inside the interrupter can effectively improve its potential distribution.

The field calculator of Ansys can be used to accurately obtain the maximum value of the field strength in the model. This method is used in this design to analyze the preliminary optimized maximum electric field strength and occurrence position, and the maximum electric field strength is 6805kV/m.

4.2.1 Influence of the Axial Dimension of the Shield on the Electric Field

In order to analyze the influence of different axial dimensions of the shielding case on the electric field intensity, the models with the axial dimension of the shielding case of 25mm, 30mm, 35mm, 40mm, 45mm and 50mm were selected. Using the same solution domain, excitation, boundary conditions and solver settings, after obtaining the calculation results of the electric field distribution, the maximum electric field intensity in the solution domain is solved by the field calculator. It is obtained that the minimum value may appear around the axial dimension of the shielding case of 30mm, so the axial dimension of the shielding case is selected to be 25mm, 26mm, 27mm, 28mm, 29mm, 30mm, 31mm, 32mm, 33mm, 34mm and 35mm to make models respectively.

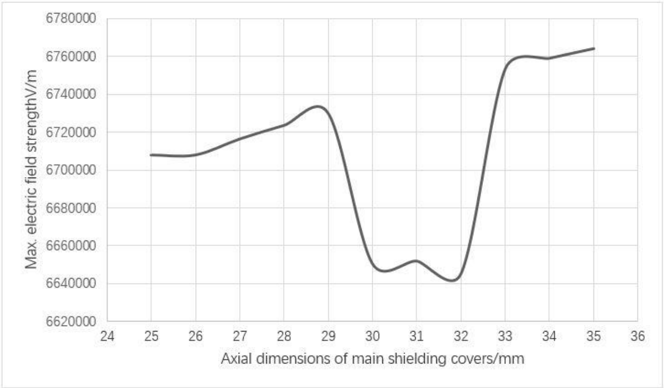



**Figure 6. The Relationship Curve between the Axial Size of the Shield and the Maximum Electric Field Strength**

It can be seen that under the same conditions, the minimum electric field intensity is obtained when the axial dimension is 32mm.

4.2.2 Influence of the Radial Dimension of the Shield on the Electric Field

Make models with radial dimensions of 24mm, 22mm, 20mm, and 18mm respectively, and use the same solution domain, excitation, boundary conditions and solver settings to obtain the calculation results of the electric field distribution. Maximum electric field strength. It can be seen that the maximum electric field intensity decreases with the increase of the radial dimension of the shield. Because the 24mm shielding cover has reached the inner wall of the insulating shell of the arc extinguishing chamber, it cannot be enlarged any further.

Under the same conditions, the minimum electric field intensity can be obtained when the radial dimension is 24mm.

In order to analyze the influence of the radial size of the shield on the overall uniform distribution of the electric field, four points N1, N2, N3 and N4 on the same plane are taken at the end points of the model contact. Take four corresponding points Point1, Point2, Point3 and Point4 at 4mm above the four points. as the Figure 7 shows.

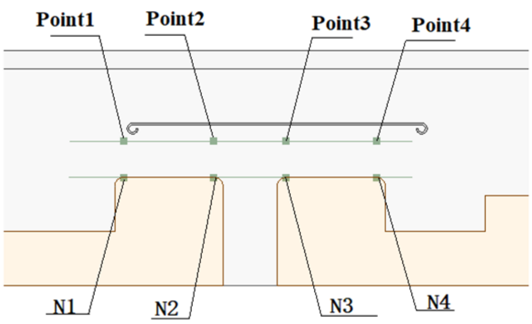



**Figure 7. Schematic Diagram of Taking Points**

Use the field calculator to calculate the electric field strength values at Point1, Point2, Point3 and Point4 under the radial dimensions of the main shield with radial dimensions of 24mm, 22mm, 20mm, and 18mm, respectively.

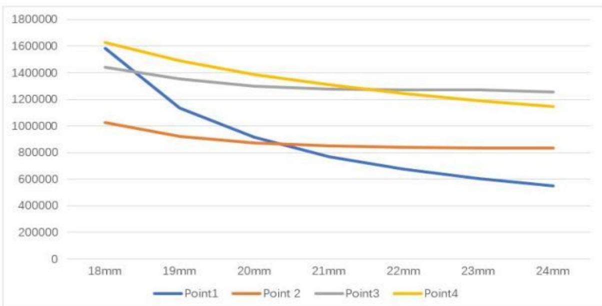



**Figure 8. The Relationship between the Electric Field Strength of the Four Measurement Points and the Size of the Main Shield**

It can be seen that the electric field in the arc extinguishing chamber is decreasing sharply except for the electric field intensity of Point1 which is closest to the maximum value of the field strength, and the values of Point2, Point3 and Point4 are getting closer with the increase of the radial length of the main shield. Therefore, it can be considered that the electric field distribution in the arc extinguishing chamber tends to be uniform.

## 5. Optimized Comparison

The potential changes between the dynamic and static contacts of the vacuum interrupter and between the contacts and the shield are relatively significant, and the electric field distribution inside the interrupter is uneven; Larger, the effective area of the contact surface will increase, and the maximum field strength inside the arc extinguishing chamber will be reduced, which can improve the internal electric field distribution.

Through the above comparative analysis, the thickness of the initially designed contact is increased to 12mm, the edge of the contact is chamfered with a radius of 1mm, the radius of the conductive rod remains unchanged, and a voltage equalizing shield is set around the static conductive rod. After the above optimization, the electric field and potential distribution are more uniform, reducing the risk of breakdown.

The structural size comparison between the original design and the optimized structure is shown in Table 1:

**Table 1. Structural Size and Maximum Electric Field Strength of Initial Design and Optimal Structure**

| | Contact Radius(mm) | Contact Chamfer Radius(mm) | Contact Chamfer Radius(mm) | Radial Length of Main Shield(mm) | Maximum Electric Field Strength(V/m) |
|---|---|---|---|---|---|
| Initial Design | 10 | none | 40 | 20 | 8917508.1309 |
| Optimized Design | 12 | 1 | 32 | 24 | 6604239.3954 |

The two-dimensional model is automatically generated into a corresponding three-dimensional model in Ansys software. The solver type is set to electrostatic field, zero potential is loaded on the moving contact, and 20kV voltage is added on the static contact. The solution area is a cube with a side length of 100mm, using adaptive meshing, and the maximum number of iterations is 15. The electric field contours of the preliminary design and optimized design are shown below. It can be seen that the electric field intensity has decreased and the electric field distribution tends to be uniform.

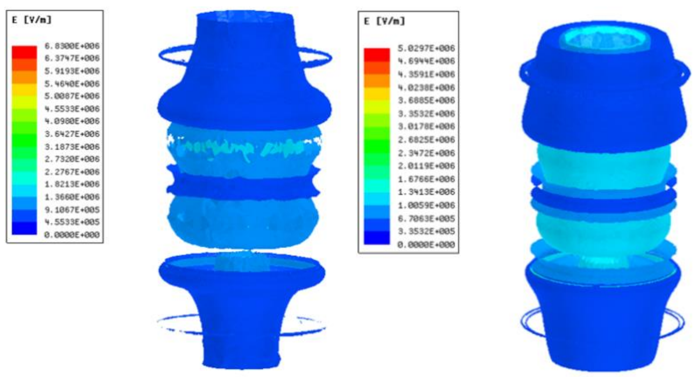



**Figure 9. Comparison of 3D Electric Field Distribution before and after Optimization**

Insert a radial section parallel to the XY plane in the middle of the contact gap with a radius of 25mm. According to the cloud image, it can be seen that the electric field intensity has dropped significantly.

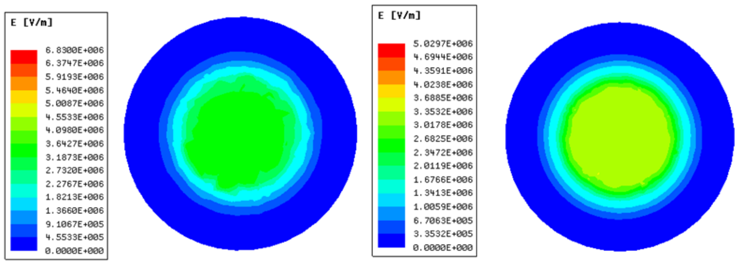



**Figure 10. Comparison of Cloud Images before and after Optimization of Contact Gap Electric Field**

In summary, it can be seen that the optimization of this design is effective.

## 6. Conclusion

In this paper, the following conclusions are obtained through the calculation and analysis of the electromagnetic field of the vacuum interrupter: (1) The radius of the conductive rod has no great influence on the insulation strength of the interrupter, as long as the mechanical strength is qualified and the reasonable configuration of other parts can be The potential is evenly distributed inside the vacuum interrupter. (2) The electric field distribution around the sharp corner of the contact is extremely uneven, so rounded corners are set. The degree of electric field inhomogeneity at the rounded corners of the contacts is greatly reduced. The thickness of the contact also affects the distribution of the electric field. The larger the thickness of the contact, the more uniform the electric field distribution. Appropriately increasing the contact thickness can increase the uniformity of the electric field. Through the above optimization, the space inside the vacuum interrupter is fully utilized, the potential concentration in a small area is avoided, and the insulation performance is improved.

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