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Original Paper

3.6kV Vacuum Interrupter Design

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Abstract

This paper analyzes and compares the principle and structure of the vacuum interrupter, so as to determine the selection of materials for the vacuum interrupter, and further compares the structural materials of the interrupter, and compares them from three angles: the shell, the contact, and the shield.

Keywords

vacuum interrupter, material, maxwell software, Insulation properties

1. Introduction

A dry gas is a good insulating medium, but when free charged particles are constantly developing in a gas, it is possible to cause the gas to gradually change into a conductor. Gaseous purity without the influence of external ionising factors is an insulator, but small amounts of impurities and charges are usually present in the gas. In the presence of an electric field generated by an applied voltage, the electric field causes charged masses to move in the same direction to form a conductive pathway, which is then broken through. Therefore most gases are not good insulating media.

Lowering the air pressure inside the vessel can produce different degrees of local vacuum, which can be used as an interrupting medium when a high vacuum is reached. In the range of 10^(-2) Pa to 10^2 Pa, the avalanche effect causes the Avalanche Multiplication and the insulation strength of the vacuum suddenly decreases as the pressure rises. In view of the technical difficulties and costs involved, vacuum interrupters are generally used in high vacuums of less than 10^(-2) Pa.

The vacuum medium is widely used in interrupters of 40.5 kV and below because of its high insulation strength, its ability to afford high currents and its ability to extinguish arcs. A reasonable design of the internal structure of the vacuum interrupter can reliably improve the insulation level of the interrupter. For vacuum interrupters with rated voltages up to 100-180 kV, the main problem of insulation is the internal electric field distribution.

In the present design of the 3.6kV vacuum contactor interrupter chamber, the following two measures are taken to improve the internal insulation performance: On the one hand, the contact structure is optimised to weaken the skin effect at the contact edge and optimise the distribution of the electric field. On the other hand, the internal shield structure was optimised to achieve a more uniform distribution of electric field and potential within the vacuum interrupter, thereby improving the insulation resistance of the vacuum interrupter.

2. Principle of the Vacuum Contactor

Contactors are switchgear designed to operate frequently under full load conditions to continuously carry rated currents in normal operation and under overload conditions. The operating mechanism of the contactor is required to be able to operate more than 50,000 times without maintenance and should be operable between 500,000 and 1,000,000 times at a given load current. They have a very high mechanical life. Under normal and overload conditions, they are able to connect, continuously carry and disconnect rated currents. Under abnormal operating conditions, they are able to carry rated short-circuit currents and corresponding peak currents for a certain period of time. As contactors do not have the ability to disconnect larger short-circuit currents, fuses or circuit breakers are usually used as back-up protection.

2.1 Principle of the Interrupter

The vacuum interrupter is the main component of the vacuum contactor. The arc extinguishing principle of the vacuum interrupter chamber is to make the vacuum circuit breaker after breaking the circuit arc in the vacuum quickly extinguished, so that the vacuum circuit breaker disconnected successfully. The operation of the vacuum interrupter chamber is accomplished by pulling the dynamic contacts inside the vacuum interrupter chamber to separate or close the static contacts by means of an operating mechanism located outside the chamber.

When the contacts are separated, the arc is maintained by the ionized metal vapor released by the cathode of the medium or the negative polarity contact. When the current is close to zero, the ionization effect disappears and the vapor cools very quickly, ensuring effective current breaking, almost Regardless of the rate of rise of the transient recovery voltage. Since there are no inelastic collisions between gas molecules, the vacuum has the fastest dielectric recovery strength after interruption of the current zero.

Due to the short arcing time, small contact gap and arc length, the arc energy dissipated in the vacuum is almost one-tenth of that, the small arc energy makes the contact ablation degree low, and the insulation requirements for the shielding cover are relatively loose. And the insulation strength can be maintained for a longer time after frequent breaking. Therefore, compared with other types of different interrupters, the vacuum interrupter requires relatively less mechanical energy to operate, so a simple and reliable operating mechanism can be used, and the operation process is less noisy.

2.2 The Structure and Material of the Arc Extinguishing Chamber

2.2.1 Housing Material Selection

The vacuum interrupter is packaged in a sealed shell, and the contacts of the vacuum interrupter, the shielding cover, the conductive rod and the support of the moving and static contacts are arranged inside. Inserting a Kovar ring between the insulating material and the metal and end cap provides a sealed link between the two.

Common shell materials for vacuum interrupters include PTFE reinforced glass, high alumina ceramics, and glass-ceramics.

The PTFE-reinforced glass shell has low cost and is easy to process. The sealing device made of this material has good airtightness and insulation strength, and at the same time has a certain mechanical strength. Although the impact strength, tensile strength and softening temperature are not as good as those of high alumina ceramics and glass-ceramics, because the interrupter is vacuum interrupted at a lower high voltage level of 3.6kV, the stress it bears is within the acceptable range of reinforced glass. Its production process is mature, the cost is far lower, and the flashover electric field strength in the air is low, so this paper chooses PTFE reinforced glass as the insulating shell material of this design

2.2.2 Contact Material Selection

During the AC breaking process, because the contact is not an absolutely smooth plane, with the separation of the contact surface, the contact area gradually decreases, and the current density increases greatly, causing the contact material to melt or even vaporize, even if the dielectric strength of the gap is restored afterwards, the contact material is also subject to loss.

When the contacts close there is a somewhat elastic bump, so sometimes several jumps back and forth occur before both contacts remain closed in the closed position, a phenomenon known as bouncing. During the bouncing process, each contact separation will be accompanied by the generation of an arc, which will cause contact erosion and even weld the contacts together, which is a physical phenomenon different from the wear of the contact material.

According to the above contact bouncing and arcing process, select the material that can reduce its influence. Contact materials have a great influence on the performance of vacuum switches. In addition to meeting the requirements of general switchgear for contact materials, they should also meet the following requirements: (1) Have sufficient breaking capacity; (2) Small cut-off current; (3) High compressive strength; (4) High resistance to fusion welding; (5) Low gas content; (6) High electrical conductivity, thermal conductivity and mechanical strength, and small grounding resistance; (7) Low electrical erosion rate; (8) Low thermal electron emission capability.

Pure metals are softer for making large, functional objects, so they are often combined with other metals to create more durable alloys. Many alloys have copper as the main component, with the addition of other metals to improve welding resistance, reduce current cut-off values, and sometimes increase mechanical strength. Chromium-zirconium copper (CuCrZr) has good electrical conductivity, thermal conductivity, high hardness, wear resistance and explosion resistance, crack resistance and high softening temperature. Suitable as contact material for arc chute.

2.2.3 Shield Material Selection

The shielding cover inside the vacuum interrupter not only plays the role of equalizing the voltage, but some can also help the contacts to stop the arc, such as the main shielding cover around the contact, the bellows shielding cover protecting the bellows, and the voltage equalizing shielding cover. Generally choose oxygen-free copper, stainless steel or nickel to manufacture. The main shield condenses the arc generated between the contacts while blocking the simultaneous generation of metal vapor and liquid droplets to prevent them from splashing around the arc extinguishing chamber. The bellows shield can prevent the molten metal droplets generated by the vacuum arc from burning or burning through the bellows. The equalizing shield can even the electric field inside the vacuum interrupter, and at the same time reduce the excessive concentration of local potential and make it more evenly distributed.

The following table gives the thermal characteristic values of some commonly used shielding materials:

Table 1. Thermal Properties of Common Shielding Materials

Material Name	Copper	Nickel	Stainless Steel	Steel
$\lambda(W/(cm \cdot ℃))$	3.85	0.68	0.21	0.41
$C(J/(kg \cdot ℃))$	381	46.1	50.2	46.1
$\rho(kg/cm^3)$	8.7×10^{-3}	9×10^{-3}	8×10^{-3}	8×10^{-3}
$\Delta W_{max}(\frac{kW}{cm^2})$	3.38	1.46	0.91	1.23
$k = (\lambda / c\rho)$	1.162	0.139	0.052	0.127
$\delta_{20}(mm)$	1.52	0.53	0.32	0.51

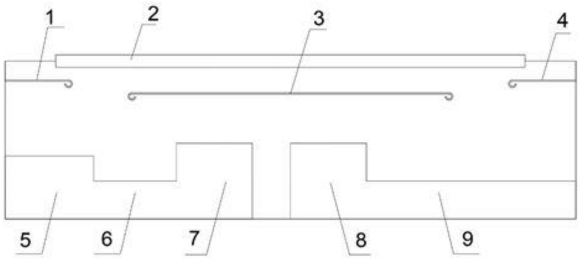
In this paper, stainless steel is selected as the material of the shield. When the number of chromium atoms mixed into steel exceeds 12.5% of the total number of atoms in the mixture, it can cause a sudden change in the potential polarity of the steel, rising from negative potential to positive electrode potential, thereby slowing down the speed of electrochemical corrosion. Its good mechanical properties can withstand certain high temperatures.

3. Research on Insulation Performance of 3.6kV Vacuum Interrupter

The insulation and withstand voltage characteristics of the vacuum interrupter refer to the withstand voltage level of the gap between the internal structures under the impact of power frequency voltage and lightning strike voltage. If the insulation level between the contacts cannot be restored after being broken down, the breaking performance of the vacuum circuit breaker will be greatly reduced. The insulation performance between the shielding cover and the conductive rod has a great relationship with the external dimensions when designing the vacuum interrupter. The insulation along the surface inside and outside the interrupter will be affected by the uniformity of the electric field distribution, so the uniform design of the electric field is very important.

All structural parts of the vacuum interrupter are basically rotationally symmetrical structures, so its internal electric field can be regarded as an axisymmetric electric field, but because the voltages applied to the dynamic and static contacts are not equal, the structure of the vacuum interrupter is symmetrical, but the potential The distribution is not symmetrical, so in the detailed calculation, half of the field along the axial section of the vacuum interrupter is taken as the entire calculation area. The arc extinguishing chamber mainly includes dynamic and static contacts, dynamic and static conductive rods, main shielding cover, end shielding cover, insulating shell and other components. etc. have been simplified.

Therefore, the entire arc extinguishing chamber can be regarded as a rotating body. Therefore, the Maxwell 2D cylindrical coordinate system is selected for modeling, and the model is completed around the Z axis. The system will default it as a rotating body around the Z axis.



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 1. Simplified Model of 3.6kV Vacuum Interrupter

4. Parameter Calculation of 3.6kv Vacuum Interrupter

According to the current Chinese standard, the experimental voltage of the external insulation of power facilities at an altitude of 1000m to 4000m is the product of the experimental voltage of the external insulation of the plain area and the altitude correction factor. This paper adopts the altitude correction formula recommended by GB311.1. The altitude correction factor in GB311.1-1997 is

$$k_a = 1/(1.1 - H'10^{-4})$$

Where H is the altitude of the installation point. The 3.6kV contactor of this design can work at an altitude of 1200m, so the test must be carried out at 20kV when the power frequency withstand voltage test is carried out according to the corrected value.

After the vacuum interrupter is manufactured, the vacuum degree should be kept above Pa, and it should not be lower than Pa when put into actual operation. However, after the vacuum interrupter is put into actual operation, due to the chronic air leakage of the internal parts, the vacuum degree in the interrupter decreases with time. According to regulations, the life of the vacuum interrupter should be more than 20 years, and the size of the insulating shell is determined by the maximum air leakage rate formula allowed by the vacuum interrupter:

$$Q_a = \frac{SK}{\Delta}(P_0 - P_1)$$

In the formula, S is the surface area of the insulating part of the shell; D is the diameter of the shell; L is the length of the shell; the atmospheric pressure outside the arc extinguishing chamber; the atmospheric pressure inside the arc extinguishing chamber; the thickness of the insulating part of the shell;

There is the following empirical formula for the contact size:

$$I = k \times D^2 \times A\%$$

In the formula, I is the limit breaking current; D is the contact diameter; A is the effective contact surface area. The contact opening distance d is related to the contact diameter D, and the two influence each other with k as the coefficient, and k varies with the opening distance.

The rated voltage of this design is 3.6kV. The axial dimension depends on the rated voltage. The length of the conductive rod of the vacuum interrupter is:

$$H = d + h + y$$

In the formula, H is the axial length; d is the contact opening distance; h is the contact thickness.

Through the heat empirical formula of the main shield absorbing the arc and the relationship between the heat absorbed by the shield and the maximum power density allowed to be absorbed by the shield, we can get the minimum value allowed by the inner diameter of the main shield:

$$D_{\min} = \frac{0.35UI}{\pi d \Delta w_{\max}}$$

In the formula, U is the arc voltage; I is the subsection current; t is the arcing time; d is the contact opening distance; W is the heat absorbed by the shielding cover; it is the maximum power density allowed to be absorbed.

After the diameter of the shield is determined, the thickness of the shield is then determined. The empirical formula is as follows:

$$\delta = \sqrt{\frac{\lambda t}{C\rho}}$$

Where, is the depth of heat penetration into the solid; is the thermal conductivity of the material; C is the specific heat capacity of the material; is the density of the material; T is the heat action time. The thickness of the main shield is equal to or slightly greater than the heat penetration depth, so that the surface temperature of the shield is basically not affected by the thickness. Because when the thickness is much larger, the temperature rise on the surface of the shield will not decrease significantly due to the increase in thickness.

The calculated dimensions of the design are as follows:

Table 2. Calculate Structure Size

Shell Radial Dimensions(mm)	50
Shell Axial Dimensions(mm)	90
Contact Distance(mm)	6
Contact Thicknessmm)	10
Contact Diameter(mm)	12
The Total Length of The Conductive rod(mm)	72
Radial Radius of Main Shield(mm)	20
Axial Dimension of the Main Shield(mm)	40
Shield Thickness(mm)	0.2

4. Magnetic Field Analysis of 3.6kv Vacuum Interrupter

Numerical methods for calculating electromagnetic fields can be divided into two categories: field segmentation method and equivalent source method. The field segmentation method includes the finite difference method and the finite element method. Because the finite element method is suitable for the calculation of electric field problems with boundaries, multi-layer media and complex boundary shapes, it can still maintain high calculation accuracy and has strong versatility. Combined with the actual situation of the vacuum interrupter, this design adopts the finite element method for numerical calculation.

Numerical Calculation of Electrostatic Field in Vacuum Interrupter Satisfies Maxwell's Equations:

$$\begin{cases} \nabla \cdot D = \rho \\ \nabla \times E = 0 \\ D = \varepsilon E \end{cases}$$

Where, is the electric displacement vector; is the bulk charge density; is the electric field strength; and is the dielectric constant. Numerical Calculation of Finite Element Electric Field to Solve Domain Boundary Conditions

$$\begin{cases} \Gamma_1: \varphi = \varphi_0 \\ \Gamma_2: \dfrac{d\varphi}{dn} = q_0 \end{cases}$$

Where is the surface satisfying the Dirichlet boundary condition; is the surface satisfying the Neumann boundary condition; is the boundary potential and is the boundary condition.

According to the set conditions, use Ansys Maxwell software to automatically generate subdivision units. Firstly, the area with the largest error is searched inside the analysis object and the mesh is refined in this area. After completing a mesh refinement process, recalculate and search for the area with the largest error, and judge whether the error in this area meets the set convergence conditions. If the convergence condition is met, the meshing is completed; if the convergence condition is not met, the next mesh refinement process is continued until the convergence condition is met or the maximum number of iterations is reached. In this paper, the energy calculation error is set to be less than 1%, and a total of 8817 grids are generated by 8 iterations. The structure is shown in the figure.

Pass	Triangles	Total Energy (J)	Energy Error (%)	Delta Energy (%)
1	1603	0.00061582	30.594	N/A
2	2191	0.00060416	13.749	1.8929
3	3001	0.00060165	12.103	0.41498
4	3925	0.00059992	5.941	0.28815
5	5104	0.00059874	4.6217	0.196
6	6637	0.00059816	2.3521	0.09788
7	8630	0.0005977	1.834	0.076846
8	11220	0.00059747	0.96151	0.038733

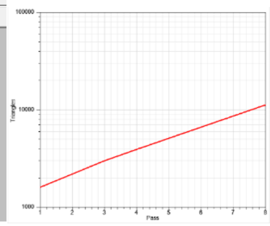


Figure 2. Meshing Results

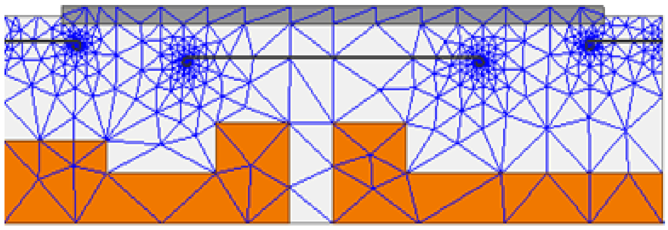


Figure 3. Meshing Effect

5. Conclusion

Through the simulation analysis and experimental research on the electric field of the 3.6kV vacuum interrupter, the following conclusions are drawn: the radial radius of the main shield is 20mm; the axial dimension of the main shield is 40mm; the thickness of the shield is 0.2mm. The contact distance is 6mm; the contact thickness is 10mm; the contact diameter is 12mm. The radial dimension of the shell is 50mm; the axial dimension of the shell is 90mm. The maximum field strength inside the vacuum interrupter is 8917kV/m.

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