Study on the Main Inner Insulation of 1100kV UHVAC Oil-gas Bushing and the Structure Optimization Design of its Fittings

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Abstract. The oil-gas bushing has the characteristics of compact structure and small floor area, which can be widely used in various voltage level substations to realize the electrical connection between transformer and high-voltage combined electrical apparatus GIS. At present, the development of oil-gas bushing for 1100kV AC extra high voltage level is the first time. It is necessary to solve the problems of the material development of main insulation core of bushing, the design and optimization of main insulation of core and the current carrying capacity of large current conductor of bushing structural design and other key technologies. This paper focuses on the analysis and calculation of the optimization design of main insulation structure of 1100kV UHV oil-gas bushing. Considering that the end of the oil-gas bushing is connected to the winding side of the transformer and the center conductor of the high-voltage combined electrical appliance in the narrow space, it is necessary to optimize the design of the structure of the fittings at both ends of the bushing to ensure that the electric field distribution is reasonable under the action of high voltage, and that it carries large current without local overheating area. Based on this, three-dimensional finite element simulation model of UHV oil-gas bushing tooling is established, and the main insulation structure of the bushing core is optimized to make its axial and radial field strength meet the control requirements. The topological structure and size of the current carrying structure in the center of the bushing and the voltage equalizing device at both ends are given, and the prototype and supporting tooling structure of the oil-gas casing are developed according to the optimized design structure, and go through various bushing type tests. In this paper, the optimized design and development of the main insulation structure of UHV oil-gas bushing, taking into account processing and installation of transformer outgoing line structure and the GIS electrical connection supporting tooling of the high-voltage combined apparatus, simulating the actual operation environment of the UHV oil-gas bushing with full voltage and full current, and carrying out the long-term performance evaluation test, has good engineering application guidance value.

Keywords. oil-gas bushing; finite element method; high voltage combined electrical appliance; matching equipment; parameter optimization.
1. Introduction
There are many applications where transformer winding is directly connected to the GIS center of high-voltage combined apparatus in various voltage grade substations. In such narrow and compact space, the oil-gas bushing can effectively realize the electrical and mechanical connection functions, so oil-gas bushing has the good engineering application value [1-3]. At present, the voltage level of China's AC substation has risen to the UHV level. There are prominent characteristics of the high voltage and high current in the above connection applications, which put forward the higher requirements for the design and development of oil-gas casings, and the development of UHV oil-gas casings is the first time in the world [4-7]. In view of this, it is urgent to solve the key technologies such as research and development of the main insulation core material of the bushing, the design and optimization of the main insulation of the bushing, and the design of the current carrying structure of the large current conductor of the bushing. This paper focuses on optimization design and calculation of the main insulation structure of 1100kV UHV oil-gas bushing, taking into account that the end of the oil-gas bushing is connected to the winding side of the transformer and the central conductor of the high-voltage combined electrical appliance[8-10] in narrow space, it is necessary to optimize design of the structure of the fittings at both ends of bushing to ensure that electric field distribution is reasonable under action of high voltage, and that it carries large current without local overheating area.

In order to achieve above goals, this paper first analyzes specific application environment of UHVAC oil-gas bushing, and puts forward the specific requirements for its contour and performance parameters. Combined with optimization design method of the bushing capacitance core, the insulation size in bushing is obtained to ensure that the axial and radial electric field strength of the bushing capacitance core can meet the requirements of electric field control and be evenly distributed. Furthermore, the three-dimensional FEM simulation model of UHV oil-gas bushing is established, and the main insulation structure of bushing core is optimized to make its axial and radial electrical field strength meet control requirements. The topological structure and size of the central current carrying structure and the end corona equalizing device of the bushing are given. According to the optimized design structure, the oil-gas bushing prototype and the supporting tooling structure are developed. In this paper, optimized design and development of main insulation structure of the UHV oil-gas bushing, taking into account the processing and installation of the transformer structure and the GIS electrical connection supporting tooling of the high-voltage combined apparatus, simulating the actual operation environment of the UHV oil-gas bushing with the full voltage and full current, and carrying out the long-term performance evaluation test, has good engineering application guidance value.

2. Field application scenario analysis of 1100kV oil and gas bushing
The key function of UHV oil and gas bushing is to connect transformer winding and GIS outgoing device of high-voltage combined apparatus [11,12], and typical installation structure is shown in Figure 1. It shows external operating environment of the oil and gas bushing is relatively narrow and compact. One end of the bushing body is immersed in transformer oil, the other end is immersed in SF6 gas under certain pressure conditions of high-voltage switch-gear GIS, and transformer winding and the important electrical equipment of the high-voltage outgoing bushing of GIS are connected respectively. In the field tooling design, the inner diameter of the gas end transition tube is 880mm, and diameter of gas end conductive rod is 180mm. And relevant operation parameters of oil and gas bushing are: the rated operation voltage Ur=1100kV, rated operation current IR=3150A, lightning impulse over-voltage BIL=2400kV, operation impulse over-voltage SIL=1950kV. Based on analysis of oil-gas bushing application scenarios, the technical problems need to be solved: 1) insulation structure design of oil-gas bushing body is reasonable, core diameter meets the compact design and the size is less than 880mm, and the radial and axial field strength distribution of the core body is uniform and meets the control requirements; 2) the current carrying structure of the conductor in the center of the bushing shall be maintained under the action of rated operation current and instantaneous short-circuit current good thermal stability; 3) reasonable design of connection structure of bushing end fittings and the corona equalizing accessories, uniform electric field distribution and good shielding effect; 4) the reasonable
design of basin insulator and GIS outgoing sleeve insulation structure in the oil gas sleeve tooling test platform, without the partial discharge, and the physical appearance of 1100kV oil gas field application supporting tooling is shown in Figure 2.

In the design of the gas end transition tube, surface field strength of central conductor in the coaxial cylindrical electric field is mainly controlled as follows:

\[
E = \frac{U_{th}}{r_1 \cdot \ln(r_2 / r_1)}
\]  

(1)

In the above formula, \(U_{th}\) is lightning impulse withstand voltage/kV. \(r_1\) is the center conductor radius/mm. \(r_2\) is shell radius/mm. When \(\ln(r_2/r_1)=1\), \(E\) is the minimum value \(E_{min}\), and the formula (1) becomes: in the above formula, \(E_1\) is the allowable lightning impulse field strength on the conductor surface corresponding to SF6 gas/kV/mm. The design value of lightning impulse withstand voltage of 220kV SF6 GIS true type test platform is 2400kV at 1.2/50μs, and the allowable lightning impulse field strength of conductor surface is 20kV/mm. Set center conductor radius \(R_1=90\)mm and shell radius
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\[ R_2 = 440 \text{mm of transition tube. Substitute the above data into equation (1) and surface field strength of the center conductor is about } 16.8\text{kV/mm. Therefore, oil and gas sleeve transition tube structure has high safety insulation margin.} \]

3. Design Analysis of main insulation structure of 1100kV oil and gas bushing

The key to the design of UHV oil-gas bushing lies in the determination of the core parameters of its main insulation capacitor [13]. The design results confirm that the number of layers of UHV oil-gas bushing pole plate is 95, the length of zero layer pole plate is 4410 mm, the diameter of conducting rod is 150 mm, the length of \( N \) layer pole plate is 1040 mm, and the diameter of \( N \) layer pole plate is 630 mm. The simulation calculation model of three-dimensional finite element tooling device for the UHP oil-gas casing is established, as shown in Figure 3.

![3D FEM model of oil and gas bushing](image)

Figure 3 shows that oil and gas sleeve and its accessories include transformer oil and SF6 gas as the insulation medium; solid insulation parts include pot insulator and sleeve capacitor core; the hardware includes central conductor and sleeve end voltage sharing shielding device. The three-dimensional finite element analysis model of corona equalizing shielding device at the end of the bushing and GIS outgoing bushing is listed in Figure 4 below.

![Key matching device model of bushing](image)

Figure 4 shows that structure of oil-gas busing supporting device is complex, and the distribution of electric field at each key position should be analyzed. Meanwhile, specific structure size of each corona equalizing device is given to coordinate with core structure of oil-gas bushing to pass various routine test items. Apply 1200kV voltage to the central conductor of oil and gas bushing, and apply zero potential to its grounding shielding layer and GIS tank. Figure 5 shows that the overall potential
distribution of oil-gas bushing is uniform, the high potential of the central conductor gradually transits to the zero potential of the GIS pipeline, and the high field strength area is mainly concentrated in the interior of the bushing core and the surface area of the accessories of the corona equalizing hood. In order to pay more attention to the distribution of electric field strength inside the oil and gas bushing core, the electric field distribution curve is intercepted on its radial path as shown in Figure 6.

Figure 6 shows that the radial field strength of the bushing core presents typical "U" distribution feature, with maximum field strength of 4.25kV/mm, which is located near the zero level electrode plate, i.e. near center guide rod. The minimum value of field strength is located near the 60th plate, which is 2.25kV/mm. The axial field intensity distribution of bushing core is basically uniform, showing a jump law, and its average value is stable around 0.715kV/mm. At the same time, focus on the distribution of electric field strength at the end of the bushing, as shown in Figure 7.
The E-field intensity distribution at the end of the bushing is the key point in the core design. Figure 7 shows that the high field intensity area at the end of the bushing is effectively covered in epoxy impregnated paper, which effectively avoids the partial discharge phenomenon in the high field intensity area at the end. Figure 7 also shows that due to the shielding effect between two adjacent plates, there is a low field strength area at the end of the plate, and at the same time, the edge effect of the plate is avoided to ablate the epoxy impregnated paper solid insulation material. Pay more attention to electric field distribution on the surface of corona equalizing device at both ends of the oil and gas bushing, as shown in Figure 8. Figure 8 shows that electric field distribution on the surface of the bushing grading cover is relatively uniform. The maximum electric field intensity on the surface of the oil and gas bushing SF6 gas end grading cover is 18.68kV/mm, and the maximum electric field intensity on the surface of the transformer oil end grading cover is 6.33kV/mm, which are lower than the control requirements of 20kV/mm. On basis of electric field analysis, the following theoretical analysis is carried out for the current carrying conductor of oil and gas bushing.

4. Calculation and analysis of 1100kV oil and gas bushing test tooling

Above-mentioned electrical and thermal field simulation analysis is carried out for 1100kV oil and gas bushing single equipment. In view of that, the oil-gas bushing needs to be equipped with supporting tooling at the type test site and in the actual operation environment, the 3D finite element tooling simulation calculation model of 1100kV oil and gas bushing will be established, and electric field verification simulation of the matching tooling and corona equalizing device will be carried out to ensure that well-designed oil and gas bushing body is in practice[14]. Types of tests have been successfully passed in operation environment, and electrical performance has high reliability in the field operation environment. The 3D simulation calculation model is shown in Figure 9.
Figure 9 shows there are many accessories for 3D tooling simulation calculation model of the oil-gas bushing, including the GIS outgoing bushing, the horizontal connecting bus, end equalizing ball, the test oil tank and other tooling. The overall potential and electric field distribution are shown in Figure 10. Figure 10 shows that internal equi-potential line of 3D tooling is compact, which is determined by strong modulation effect of pole plate at the end of the bushing. The high field strength area is mainly concentrated on the corona equalizing device at the end of bushing and the surface of the central connecting conductor. The electric field strength distribution at the above key positions is shown in Figure 11. Figure 11 shows that the electric field intensity on the surface of the corona equalizing cover at the end of the oil-gas bushing is 11.24kV/mm and 11.42kV/mm respectively, which is lower than the set control field intensity value. Further, pay attention to the electric field simulation results of the outgoing bushing of GIS, and list the electric field strength distribution at the typical bolt location in Figure 12.
Figure 12 shows typical bushing bolt is in the high potential area, and chamfering is carried out in area 1, area 2 and area 3 in the design, and the high field strength appears in the above three chamfering areas, with value of 19.68kV/mm, meeting field strength control requirements. Modeling and verification are carried out for GIS outgoing bushing fittings, as shown in Figure 13.

Figure 13 shows that the conductor end grading cover at the junction of outgoing bushing can effectively shield the high field strength area, and the maximum field strength of the end grading cover is lower than 20kV/mm, which meets control requirements. For the insulation structure of the bushing, the check calculation is generally carried out under the lightning impulse testing voltage, so the E-field simulation of insulation structure is carried out by applying the lightning impulse test voltage.
Figure 14 shows that the distribution of equi-potential lines of the composite bushing. From the results of the electric field simulation, it can be concluded that under lightning impulse voltage of 2400kV, the maximum E-field strength of 1100kV gas filled composite bushing is 19976V/mm at center guide rod, 3705V/mm at the surface of grading ring, 2262V/mm at the surface of bushing sheath, and 10066V/mm at the flange of metal shield inside bushing, as shown in the Figure 15.

![Central Guide Rod, Grading Ring, Sheath Surface, Metal Shield](image1)

**Fig.15** Distribution of electrical stress in key parts

![Surface Potential Distribution of Sheath](image2)

**Fig.16** The surface potential distribution of sheath

Figure 16 shows the potential distribution on the surface of the sheath, which shows that the potential distribution on the surface of the sheath is basically linear due to the modulation of metal shield inside sheath. Figure 17 shows the distribution of electric field at 1.5m above the ground, indicating that the distribution of the electric field is inverted "U" type, and the maximum electric field strength at 4.65m away from bushing is 7.95kV/m.

![Electric Field Distribution at 1.5m Off the Ground](image3)

**Fig.17** Electric field distribution at 1.5m off the ground
5. 1100kV oil and gas bushing and overall tooling field test

UHV oil and gas bushing prototype shall be subject to type electrical performance test according to standard GB/T4109-2008 for insulating bushing with the AC voltage higher than 1000V, and the test site is shown in Figure 18.

![Fig.18 On-site type test of UHV oil-gas bushings](image)

The oil end of the bushing is put into the transformer oil barrel, and the gas end is put into GIS pipeline. Test high voltage is connected with the oil and gas bushing prototype through the gas bushing. For the measurement of dielectric loss factor and capacitance of bushing core, standard stipulates that the measured value of bushing shall not exceed 0.5% under power frequency voltage of 120kV, 300kV and 667kV. Under the power frequency dry withstand voltage test, processing frequency withstand voltage of bushing high voltage terminal to ground shall be 1200kV, lasting for 5min, and there will be no flash-over or breakdown. During measurement of partial discharge, when the measured voltage is 953kV, there shall be partial discharge. The quantity shall be less than 10pC, when the measured voltage is 667kV, the local discharge shall be less than 5pC. For the lightning impulse dry withstand voltage test, the peak value/times of the lightning full wave withstand voltage: the 2400kV(positive polarity)/15 times, 2400kV(negative polarity)/15 times, the peak value/times of the lightning cut-off withstand voltage: 2760kV(negative polarity)/5 times, without the flash-over or breakdown. For the operation impulse dry withstand voltage test: the operation full wave withstand voltage: voltage peak value/times, 1950kV (positive polarity)/15 times, no flash-over or breakdown.

6. Conclusion

The radial field strength of oil and gas bushing core presents typical "U" distribution feature, with the maximum field strength of 4.25kV/mm, which is located near the zero level plate, i.e. near the center guide rod. The minimum value of the field strength is located near the 60th plate, which is 2.25kV/mm. The axial field intensity distribution of bushing core is uniform and stable near 0.715kV/mm. Moreover, the maximum electric field intensity on the surface of the corona equalizing cover at the gas end of the oil and gas sleeve SF6 is 18.68kV/mm, and the maximum electric field intensity on the surface of the corona equalizing cover at the oil end of the transformer is 6.33kV/mm, which is lower than the control requirements of 20kV/mm.

The electrical performance type test results of the UHV oil and gas bushing and supporting tooling structure developed and designed show that prototype meets the test requirements, and prove that the main insulation structure and supporting test device of the designed oil and gas bushing can be designed reasonably under UHV voltage level, and electrical performance meets various requirements.

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