Thermal Performance and Insulation Structure Design of ±400kV Valve Side Bushing of Converter

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Abstract. The design features of inner and outer insulation structure of valve side bushing of ±400kV converter transformer are representative. Its main insulation structure type and design method are basically consistent with those of ±800kV converter transformer valve side bushing in China, but its design margin is lower than that of UHV converter transformer bushing, and the valve side bushing of ±400kV converter transformer is used more in converter valve hall, so its insulation structure design and engineering should be It is necessary to analyze and discuss the insulation structure design of valve side bushing of ±400kV converter transformer. In this paper, ±400kV converter transformer valve side bushing insulation accident is analyzed in detail, from which the specific causes of insulation failure are summarized, providing reference for the design of internal and external insulation structure of converter transformer bushing. Based on this, this paper first analyzes the heating mechanism of the double guide rod structure of the converter bushing, gives the design size of the double guide rod structure from the theoretical analysis point of view, further optimizes the core insulation structure of the converter bushing, and gives the external insulation design scheme of the converter bushing from the perspective of internal and external insulation coordination, and checks and calculates the overall electric field distribution. The radial electric field strength is controlled at 3.11kV/mm under working voltage and 0.51kV/mm under power frequency withstand voltage, which meet the requirements of electric field strength control in the design of ±400kV converter bushing. Furthermore, the valve side bushing of the developed ±400kV converter transformer is tested, and typical type tests such as power frequency dry withstand voltage test and partial discharge measurement, lightning impulse dry withstand voltage test and partial discharge measurement and temperature rise test are passed. The research results of this paper theoretically give the control requirements for the field strength design of the valve side bushing of converter transformer, and optimize the design size of its double guide rod structure, and develop a prototype to prove the effectiveness and reliability of the theoretical analysis. The above research results have good theoretical guidance value and practical significance for the insulation structure design and operation state maintenance of valve side bushing of ±400kV converter transformer.

1. Introduction
A capacitor core is added between the conductive tube (rod) and the flange as the internal insulation. There are multi-layer metal plates in the insulation layer of the capacitor core to force the electric field uniformity inside and on the surface of the bushing[1-4]. The insulation performance of capacitor bushing mainly depends on the capacitor core. The typical dry bushing of capacitive converter is
mainly composed of conducting rod, connecting sleeve, capacitor core, composite sleeve, grading ring (ball), etc., and its structure is shown in Fig. 1.

![Fig.1 Schematic diagram of capacitive converter dry bushing](image)

1—terminal block; 2—Grading ring; 3—Current carrying structure; 4—Composite coat; 5—Capacitor core; 6—Connecting sleeve; 7—Equalizing hood

The main insulation of capacitor bushing is a series concentric cylinder capacitor (i.e. a cylindrical capacitor core) composed of multilayer aluminum foil wrapped around the central conductive tube of the bushing as the electrode plate and corrugated paper as the insulating medium between the plates. One end of the capacitor is connected with the central conducting tube, and the other end is led out by the measuring terminal. After the capacitor core is rolled up, vacuum drying treatment is carried out to dry the dry electricity. The core and epoxy resin are poured and cured. After curing, the two ends of the core are cut into conical shape[5,6]. The current carrying connection mode of UHV converter bushing is conduit current carrying structure. The so-called conduit current carrying means that the conducting pipe (rod) is connected with the upper and lower terminal blocks, and can carry current directly through the conducting tube, which can bear large current; the conductive pipe is generally high-quality hard copper pipe or hard aluminum tube, and the cross-section of copper tube can be selected according to the current density of no more than 2.5A/mm², otherwise, the excessive current density will cause the conduction current to generate large heat. At the same time, in order to reduce the eddy current and hysteresis heat of metal accessories exceeding the specified value, the non-magnetic material of brass is usually used for conducting pipe[7,8]. In the following, the heating models of the core and current carrying structure of the converter under high harmonic load are established by theoretical formula.

The design features of inner and outer insulation structure of valve side bushing of ±400kV converter transformer are representative. Its main insulation structure type and design method are basically consistent with those of ±800kV converter transformer valve side bushing in China, but its design margin is lower than that of UHV converter transformer bushing, and the valve side bushing of ±400 kV converter transformer is used more in converter valve hall, so its insulation structure design and engineering should be It is necessary to analyze and discuss the insulation structure design of valve side bushing of ±400kV converter transformer. In this paper, the ±400kV converter transformer valve side bushing insulation accident is analyzed in detail, from which the specific causes of insulation failure are summarized, providing reference for the design of internal and external insulation structure of converter transformer bushing. Based on this, this paper first analyzes the heating mechanism of the double guide rod structure of the converter bushing, gives the design size of the double guide rod structure from the theoretical analysis point of view, further optimizes the core insulation structure of the converter bushing, and gives the external insulation design scheme of the converter bushing from the perspective of internal and external insulation coordination, and checks and calculates the overall electric field distribution. Further, the valve side bushing of the developed ±400kV converter transformer is tested. The above research results have a certain theoretical and practical application value for the operation, maintenance and overhaul of converter bushing.

2. Selection of radial allowable field strength for capacitor core of dry type bushing with capacitive converter

In fact, the inner plate of converter bushing core has a certain thickness. Assuming that there is voltage between two adjacent plates[9,10], a uniform electric field will be established between the two plates:
\[ E_0 = \Delta U / d \]  
\[ E_{\text{max}} \] will appear at the end of each plate, and to \( E_{\text{max}} \) and \( E_0 \), there is a relationship as follows:

\[ E_{\text{max}} = K' \frac{2}{\sqrt{\pi}} \cdot E_0 \sqrt{\frac{d}{\Delta t}} \]  

Where: \( K' \) — Correction factor. The above formula is the quantitative relationship between the maximum field strength at the edge of the plate \( E_{\text{max}} \), insulation thickness \( d \) between plate and electrode \( \Delta t \). For the converter bushing, the radial breakdown inside the capacitor core generally starts from the harmful partial discharge at the edge of the electrode plate[11]. The microscopic observation of the electrode edge is shown in Fig. 2.

When the maximum field strength at the edge of the plate reaches the breakdown field strength \( E_B \) of the epoxy impregnated paper material in the bushing core, partial discharge occurs:

\[ E_B = K' \frac{2}{\sqrt{\pi}} \cdot E_i \sqrt{\frac{d}{\Delta t}} \]  

Where: \( E_i \) — the initial field strength of partial discharge between plates. From the formula, it can be concluded that:

\[ E_i = K_H / \sqrt{d} \]  

Through the above theoretical analysis, it can be seen that the partial discharge in the bushing core is mainly caused by the maximum electric field strength at the edge of the electrode plate reaching the breakdown field strength \( E_B \) of the epoxy impregnated paper material. The maximum field strength at the edge of the plate and \( E_B \) jointly determine the edge discharge of the plate[12,13]. For epoxy impregnated paper material used in converter bushing, the specific value of \( K_H \) can be determined by test as \( K_H = 34.13 \text{kV} \cdot \text{mm}^{-1} \), as shown in Fig. 3. In the bushing design, the distance between plates is
generally between 1~5mm, which can be calculated by substituting \( d = 5 \) mm into formula: \( E_i = 15.26 \text{kV} \cdot \text{mm}^{-1} \). The maximum radial working field strength of converter bushing should have a larger safety margin. If the margin is 1.5 times, the allowable radial field strength of the converter bushing core is \( 10.2 \text{kV} \cdot \text{mm}^{-1} \) under AC condition, which is suitable for power frequency dry withstand test voltage \( U_{AC} \). Taking \( d = 5 \) mm into the equation, the breakdown field strength \( E_b \) of epoxy impregnated paper material is 26.3 kV mm\(^{-1}\), so the radial allowable field strength is far less than that of epoxy impregnated paper material. In the type test, the converter bushing should be tested for 2h DC test voltage \( U_{DC} \), so the allowable radial field strength of converter bushing core under DC condition should also be determined. The DC breakdown field strength of epoxy impregnated paper material is as high as 163 kV mm\(^{-1}\), and the possibility of inner core breakdown is very small under DC condition.

### 3. Relationship between loss and heating of dry bushing of capacitive converter and operation accident

Fig. 4 shows the insulation failure of the core of the converter dry-type bushing during operation, which shows that the core of the bushing is cracked and there are obvious traces left by arc ablation. Fig. 5 is the micrograph of the local breakdown point found in the bushing core. It can be seen that there are cracks around the breakdown point, and the wrinkled paper and epoxy resin in the core peel off each other, indicating that the insulation failure of the bushing is caused by excessive temperature, and the cracks in the core are directly related to the thermal expansion of the material caused by the sudden increase of heat value.

![Fig. 4 insulation failure of converter dry bushing in actual operation](image)

(a) Current carrying copper pipe (b) bushing core

![Fig. 5 microscopic observation on local breakdown point of casing core](image)

(a) Local breakdown point (b) Epoxy resin and crepe paper peeling

The powder samples on the surface of insulating core at the end of bushing are collected for subsequent test and analysis when disassembling the converter bushing with insulation accident. The surface state of the accident casing tail and the position where the powder is collected are shown in Fig. 6. It is shown in the figure that the surface of the equalizing ball at the end of the casing is seriously eroded by the arc, and the arc development trace can be observed at the tail of the casing core. A large amount of powder was found at the flange of the bushing tail. It can be seen that a penetrating discharge channel is formed between the high potential equalizing ball and the grounding flange due to the gradual development of the arc[14]. The short-circuit current releases a large amount of heat in a short time, resulting in a sudden rise in temperature, which leads to irreversible insulation damage at the end of the bushing. In order to further verify the thermal collapse of casing core during the accident, field emission environmental scanning electron microscope was used to analyze the
morphology and material energy spectrum of the collected core surface powder. The morphology analysis results are shown in Fig. 7 and the energy spectrum analysis results are shown in Fig. 8.

![Fig. 6 material object of accident casing core tail](image1)

![Fig. 7 powder morphology analysis of core surface](image2)

![Fig. 8 powder energy spectrum analysis of core surface](image3)

The energy spectrum analysis of the powder on the surface of the core shows that the powder contains a lot of fluorine and aluminum. The fluorine element is mainly the decomposition product of SF6 gas inside the casing, and the aluminum element is mainly the product after the equalizing ball is ablated by arc. The above chemical reaction needs to be carried out under the high temperature environment of 300 ~ 400 ℃, so the temperature suddenly rises when the accident occurs. The above theoretical analysis provides an idea for the overall structure design of valve side bushing of 400kV converter transformer, and the selection of radial allowable field strength of capacitor core of dry-type bushing of capacitor converter transformer provides the electric field strength control standard for the main insulation design of capacitor core. The analysis of the relationship between the loss and heating of the dry-type bushing of the capacitor type converter and the operation accident shows that the tail of the converter bushing is an insulation weak link, and the insulation strength design of this part needs to be strengthened. On the other hand, considering the risk of thermal breakdown of the main insulation of the bushing core, the heat dissipation of the converter bushing should be effectively considered in the design.

4. Relationship between loss and heating of dry bushing of capacitive converter and operation accident

On the connection between the current carrying terminal in oil and the inner conducting tube, the ± 400kV rubber impregnated paper converter bushing uses Swiss MC electric connection strap finger structure to connect conduction current. There are three watch bands used, each of which can carry 2000A current. The utility model has the advantages of convenient and reliable installation. In order to ensure good electrical contact and reduce heating, both contact surfaces are silver plated[15]. Since the temperature range of the casing is from -40℃ to +90℃, the central conducting tube of the casing is made of red copper with a linear expansion coefficient of 17.2×10⁻⁶/℃, and the outer material is
aluminum, epoxy, silicone rubber, etc. the inner and outer pipes are fixed at the lower end of the casing. When the central conducting pipe of the casing is heated with current, it can be extended upward to avoid the stress on the inner pipe. In the design of casing current carrying structure, it is generally necessary to calculate the current carrying density of each current carrying component. The calculation of current carrying density is shown in Formula 5.

\[ J = \frac{I}{S} \quad (5) \]

Where: \( J \) —— Current carrying density; \( I \) —— Rated current, 5515 A here; \( S \) —— Current carrying contact area or conductor cross-sectional area. The cylinder diameter of the terminal in oil is 70 mm, and the current carrying cross-sectional area is calculated as follows:

\[ S = \pi \times \left( \frac{70}{2} \right)^2 = 3846.5 \text{ mm}^2 \quad (6) \]

Substituting it into formula (6), it is obtained that:

\[ J = \frac{I}{S} = \frac{5515}{3846.5} = 1.43 \text{ A/mm}^2 < 2.5 \text{ A/mm}^2 \quad (7) \]

Substituting the formula (7), it is concluded that the current carrying conduit is hollow structure, the diameter of the thinnest position is 100 mm and the inner diameter is 75 mm.

\[ S = \pi \times \left( \frac{100}{2} \right)^2 - \left( \frac{75}{2} \right)^2 = 3434 \text{ mm}^2 \quad (8) \]

Substituting into Formula (8):

\[ J = \frac{I}{S} = \frac{5515}{3434} = 1.6 \text{ A/mm}^2 < 2.5 \text{ A/mm}^2 \quad (9) \]

The cylinder diameter of the current carrying terminal in air is 100 mm and the length is 250 mm. The current carrying contact area is calculated:

\[ S = \pi \times \left( \frac{100}{2} \right)^2 \times 250 = 78500 \text{ mm}^2 \quad (10) \]

Substituting it into Formula (10), it is obtained that:

\[ J = \frac{I}{S} = \frac{5515}{78500} = 0.07 \text{ A/mm}^2 < 0.3 \text{ A/mm}^2 \quad (11) \]

In the design of casing current carrying structure, it is generally necessary to calculate the current carrying density of each current carrying component. Generally, the allowable current carrying density \( j \) is: surface contact density \( \leq 0.3 \text{ A/mm}^2 \), conductor section density \( \leq 2.5 \text{ A/mm}^2 \). Through data calculation, the current carrying design of casing can meet the requirements, and the actual current carrying capacity can be verified by temperature rise test.

5. Design of main insulation structure of dry bushing for capacitive converter

According to the AC test parameters of power frequency withstand voltage of 650 kV, lightning impulse full wave withstand voltage of 1365 kV and lightning impulse chopping withstand voltage of 1570 kV, three methods of equal margin, equal capacitance and equal thickness are used to calculate and design the capacitor core. The plate layout is optimized by the equal margin design method, and the calculation is conducted according to the principle of conductivity distribution of insulating materials under DC voltage. The radial and axial field strength and other parameters of the capacitor core are calculated. The maximum allowable radial field strength under AC voltage is calculated by the formula:
Where: \( E_{rm} \) —— Maximum allowable radial field strength under AC voltage; \( K_1 \) —— The scale factor is 17; \( \varepsilon_r \) —— The dielectric constant is 4.1; \( d \) —— The minimum insulation thickness is 1.9.

According to formula (12), the theoretical value of allowable field strength under AC voltage is obtained: \( E_{rm} = 4.0 \text{kV/mm} \). In the core calculation, the electrode diameter can be determined first, thus the electrode diameter ratio can be obtained.

\[
\xi_r = \frac{D_n}{D_0} \quad (13)
\]

Where: \( \xi_r \) —— electrode diameter ratio; \( D_n \) ——The diameter of the outermost electrode is 425; \( D_0 \) ——The diameter of the outermost electrode is 425, and that of the innermost electrode is 156:

\[
\xi_r = \frac{D_n}{D_0} = \frac{425}{156} = 2.72 \quad (14)
\]

In the calculation of electrode length, the electrode length should be adjusted continuously to make the electrode length ratio approach to the electrode diameter ratio.

\[
L_n = L_t + L_{sb} + L_{xn} \quad L_0 = L_n + \Sigma_{\text{up}} + \Sigma_{\text{down}} \quad \xi_1 = \frac{L_0}{L_n} \quad (15)
\]

Where: \( L_n \) ——The length of the outermost electrode; \( L_t \) —— The length of middle fittings is 2255; \( L_{sb} \) —— The length of upper shield is 413; \( L_{xn} \) —— The length of the lower shield is 20; \( L_0 \) —— Length of innermost electrode; \( \Sigma_{\text{up}} \) —— The length of upper step of core body is 2478; \( \Sigma_{\text{down}} \) —— The length of the lower step of the core body is 1291; \( \xi_1 \) —— Electrode diameter ratio. The length of the outermost electrode was calculated \( L_n = L_t + L_{sb} + L_{xn} \) =2688mm. Length of zero electrode:

\[
L_0 = L_n + \Sigma_{\text{up}} + \Sigma_{\text{down}} = 2688 + 2478 + 1291 = 6457 \text{mm}. \quad \text{Final adjusted} \quad \xi_1 = \frac{L_0}{L_n} = \frac{6457}{2688} = 2.4
\]

Through the above formula calculation, the obtained parameter values are input into the program of high voltage bushing internal insulation optimization design software package, and the electric field strength of each layer electrode of capacitor core is calculated by computer:

| Table 1 Calculation results of internal insulation optimization design software package for high voltage bushing |
|---------------------------------------------|
| N  | DL_n | DL_1 | SDL_n | AL | EL_n | EL_1 | ER | D  | S | d  |
|-----|------|------|-------|----|------|------|----|----|---|----|
| 1   | 22   | 42   | 160   | 6393 | .51  | .26  | 3.11 | 159.8 | 502 | 1.9 |
| 5   | 21   | 40   | 246   | 6143 | .5   | .26  | 2.95 | 175.0 | 549.8 | 1.9 |
| 7   | 21   | 39   | 288   | 6022 | .49  | .26  | 2.88 | 182.6 | 573.7 | 1.9 |
| 10  | 20   | 38   | 348   | 5846 | .5   | .26  | 2.77 | 194.0 | 609.5 | 1.9 |
| 17  | 19   | 36   | 482   | 5455 | .5   | .26  | 2.62 | 220.6 | 693  | 1.9 |
| 22  | 20   | 38   | 583   | 5160 | .5   | .26  | 2.53 | 241.6 | 759  | 2.1 |
| 25  | 20   | 38   | 643   | 4986 | .49  | .26  | 2.49 | 254.2 | 798.6 | 2.1 |
| 28  | 19   | 37   | 701   | 4816 | .51  | .26  | 2.45 | 266.8 | 838.2 | 2.1 |
| 32  | 19   | 37   | 777   | 4592 | .51  | .26  | 2.42 | 283.6 | 891  | 2.1 |
| 35  | 19   | 36   | 834   | 4424 | .5   | .26  | 2.40 | 296.2 | 930.5 | 2.1 |
| 37  | 22   | 42   | 875   | 4307 | .5   | .26  | 2.40 | 305.3 | 959.1 | 2.45 |
| 40  | 22   | 42   | 941   | 4115 | .5   | .26  | 2.39 | 320.0 | 1005.3 | 2.45 |
| 45  | 19   | 36   | 1039  | 3831 | .5   | .27  | 2.40 | 341.7 | 1073.5 | 2.1 |
| 50  | 19   | 37   | 1134  | 3551 | .51  | .26  | 2.44 | 362.7 | 1139.5 | 2.1 |
| 55  | 20   | 38   | 1232  | 3265 | .5   | .26  | 2.50 | 383.7 | 1205.4 | 2.1 |
| 60  | 21   | 40   | 1333  | 2969 | .49  | .26  | 2.61 | 404.7 | 1271.4 | 2.1 |
| 65  | 20   | 38   | 1429  | 2688 | .5   | .26  | 2.75 | 423.7 | 1331.1 | 1.9 |
According to the calculation results in Table 1, it can be seen that the maximum radial field strength of capacitor core appears on the first layer plate close to the conducting tube under the highest working phase voltage of 341kV. The actual calculation result is that under AC voltage = 3.11kV/mm, the minimum value appears in the plate of the 40th layer, 60s Under the power frequency withstand voltage, the field strength of the upper and lower axial directions of the capacitor core does not change with the increase of the number of plate layers, and both of them are controlled within the range of empirical allowable field strength. According to the calculation results in Table 2, the maximum value of the radial field strength of the capacitor core still appears on the first layer plate close to the conductive tube under the 60s power frequency voltage of 650kV. The actual calculation result is $3.11kV/mm$, the minimum value appears in the plate of the 40th layer, and the maximum value of the radial field strength appears under the lightning impulse withstand voltage. In the innermost layer, the minimum value of the starting voltage is 20.7 kV/mm, which is far less than the breakdown voltage. The closer to the conducting rod, the higher the voltage between the electrodes.

| Table 2 Main calculation results of capacitor core |
|--------------------------------------------------|
| Under working voltage | Power frequency withstand voltage under 650kV axial field strength | Power frequency withstand voltage under 650kV radial field strength | Radial field strength under full wave lightning impulse withstand voltage of 1365kV |
|------------------------|--------------------------------------------------|--------------------------------------------------|--------------------------------------------------|
| 3.11kV/mm              | 0.51kV/mm                                        | 5.93kV/mm                                        | 12.45kV/mm                                       |

It can be seen from the results in Table 2 that the maximum value of radial field strength appears on the plate near the conducting tube. The actual calculation result is that under AC voltage = 3.11kV/mm, which is 4.0kV/mm lower than the allowable calculation result, and the theoretical design is passed. The working voltage, power frequency withstand voltage and electric field strength under lightning impulse withstand voltage are all less than the design experience value and the specified requirements.

From the statistical data, it can be found that the axial field strength under power frequency withstand voltage calculated by the three methods is basically the same, ranging from 0.50 kV / mm to 0.51 kV / mm, and the minimum calculation result of radial field strength equal margin method under operating voltage is 3.11. The results of partial discharge starting voltage and sliding flashover starting voltage calculated by equal margin method are the highest. The higher the voltage is, the better the core is, and the less likely the core is to flashover. Therefore, the capacitor core designed by equal margin design method after optimization design has the advantages of large margin, high initial voltage of partial discharge and initial voltage of sliding discharge. According to the distribution of plates calculated by this method, the capacitor core is rolled.

6. Checking calculation of main insulation of dry bushing for capacitive converter

The dynamic process of the electric field distribution in the bushing and the mechanism of the charge migration, recombination and distortion electric field should be considered in the design. Under the AC voltage of 527 kV for 1 h, the calculation results of potential, electric field distribution and field strength of ±400 kV converter transformer bushing with epoxy impregnation dry structure are as follows:
It can be seen from Fig. 9 and Fig.10 that the voltage at the head equalizing ring, inner guide rod and tail crimping ball is the highest, and the potential is centrosymmetrically distributed in the space. It can be seen from Figure that the electric field strength of the core guide rod, tail equalizing ball and head equalizing ring is higher, and the shielding effect of grading ring makes the electric field at the terminal block of the casing head lower.

It can be seen from the curve obtained in Fig. 11 and Fig. 12 that the radial field strength of the conducting rod is the highest, about 6.7kv/mm. With the increase of the diameter of the capacitor core, the radial field strength it bears decreases continuously, and the minimum value is 4.0kv/mm. The electric field at the outermost plate is slightly higher than that at the 42 layer electrode. As can be seen from Fig. 11, from the innermost plate to the outermost plate, under the AC voltage of 527kV, the axial field strength curve of the bushing changes more smoothly, and the lower axial field strength is always higher than the upper axial field strength. The maximum axial field strength value of the capacitor core is about 0.40kV/mm, that of the capacitor core is about 0.43kV/mm. The electric breakdown strength of epoxy resin used in this bushing is 29 The electric breakdown strength of insulating paper is 43kV/mm. The bushing withstands 527kV for a short time during the test, and the capacitor core can fully withstand the axial and radial field strength obtained under this voltage.

The following is about the test of ±400kV rubber impregnated paper converter bushing in the national quality supervision and inspection center of insulator arrester: firstly, all the bushing are tested one by one, and the type test is conducted after passing the test. The project sequence and results are shown in Table 3. The DC test items are all conducted on the outgoing line device simulating the actual operation state of transformer.

| Term Number | Test items | Test results | conclusion |
|-------------|------------|--------------|------------|
| 1           | Power frequency dry withstand Voltage test and partial discharge measurement | 527kV maintain 5min PD ≤ 5.2pC | PASS |
|             |            | 650kV maintain 5min PD ≤ 6.5pC |           |
|             |            | 527 kV maintain 1 h partial discharge ≤ 5.5 pC |           |
## 7. Conclusion

The overall structure, sealing and current carrying structure of ±400kV rubber impregnated paper converter bushing are optimized, and reliable current carrying structure of head and tail seal, middle clamping structure and direct current carrying structure of conductive pipe are designed. The product has reasonable design, high mechanical strength, good seismic performance, excellent thermal stability, reliable insulation and small partial discharge. The comprehensive technical performance has reached the international advanced level, which can completely replace the imported ones and meet the requirements of localization of dry-type converter bushing.

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