Experimental Study on Surface Electric Field Distribution and Flash-over Voltage of Bushing Composite Insulator at High Altitude

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Abstract. At present, the high voltage bushing composite insulator is widely used in AC/DC system substation, and its structural parameters show the nonlinear growth trend with the increase of voltage level. Therefore, in 1000kV UHVAC and 800kV UHVDC system, bushing composite insulator has the typical characteristics of long insulation distance and large radial diameter. At present, with the proposal of high-voltage power equipment compact optimization design scheme, the radial diameter of the composite insulator for bushing can be effectively reduced by reasonable design of internal capacitor core or metal shield structure optimization design scheme, so as to realize its large aspect ratio compact design. On the other hand, the insulation distance of high voltage bushing composite insulator will be further increased when it is applied in high altitude area. The innovation of this paper is how to carry out flashover voltage test to fill the current test data gap. In view of this, this paper first establishes two typical structures of the high voltage bushing composite insulators, including the three-dimensional finite element models of the composite insulators for capacitive core converter transformer bushing and the double-layer metal shield through the wall bushing, obtains the distribution characteristics of typical voltage and electric field under the operating state, and analyzes the local high field strength and corona, the electric field distribution of composite insulators for bushing. Furthermore, the actual flashover tests between large fittings air metal grounding body and large fittings composite insulator metal grounding body are carried out in the laboratory environment, and the quantitative relationship curve between flashover voltage and space net distance is obtained. Based on the above theoretical analysis and test data, the size altitude correction and umbrella skirt contour topology optimization of composite insulator for the UHV AC/DC bushing are carried out. Finally, the DC withstand voltage test and one minute power frequency withstand voltage test are passed, which proves the rationality and effectiveness of the design of composite insulator for bushing at UHV level. In this paper, starting from the typical electric field distribution characteristics of all kinds of composite insulators for bushing, the flashover law is studied for the first time, and the flashover test is carried out in the laboratory to supplement the classical test data. The research results have good theoretical and practical significance for installation, design and operation maintenance of all kinds of composite insulators.

1. Introduction

At present, composite insulator is widely used in AC/DC system substation, including composite insulator for line, composite insulator for substation bushing and other power equipment. With the
increase of voltage level, its structural parameters show a nonlinear growth trend, especially in 1000kV UHV AC and 800kV UHV DC system[1-4]. The composite insulator for bushing has the typical characteristics of long insulation distance and large radial diameter. At present, with the proposal of high-voltage power equipment compact optimization design scheme, the radial diameter of composite insulator for bushing can be effectively reduced by reasonable design of internal capacitor core or metal shield structure optimization design scheme, so as to realize its large aspect ratio compact design. However, there is no capacitor structure to modulate the voltage distribution inside the line composite insulator, which can only meet the demand of voltage type by lengthening the space net distance of composite insulator[5-8]. On the other hand, the insulation distance of high voltage composite insulator will be further increased when it is applied in high altitude area. In the insulation structure design, the altitude correction factor $K$ is introduced to check the space net distance length of composite insulator. Therefore, this paper focuses on the characteristics of the surface voltage and electric field distribution of the composite insulator for extra long high altitude line and bushing, and how to carry out the flashover voltage test and reasonably predict and expand the test data to fill the current test data gap.

In view of this, this paper first establishes three typical structures of composite insulators for high-voltage line and bushing, including traditional power transmission line, bushing of capacitor core converter transformer and the double-layer metal shield through the wall bushing. The quantitative relationship between local high field strength, voltage distribution curve, corona inception voltage and flashover voltage of composite insulator for line and bushing is analyzed. Furthermore, the actual flashover tests between large fittings air metal grounding body and large fittings composite insulator metal grounding body are carried out in the laboratory environment, and the quantitative relationship curve between flashover voltage and space net distance is obtained. Based on the above test data, the application of grey system algorithm for high-precision nonlinear fitting and wide area data prediction can effectively avoid the complex and repetitive large-scale composite insulator withstand voltage test, and improve the optimization design efficiency of composite insulator for line and bushing in practical engineering.

Based on the above theoretical analysis, test data and grey system fitting prediction method, the size altitude correction and the umbrella skirt contour topology optimization of composite insulator for UHVDC bushing are carried out. Aiming at the high altitude application scenario of composite insulator for bushing, the altitude correction factor $K$ is used to correct the topological structure size. Finally, the type tests such as DC withstand voltage test and one minute power frequency withstand voltage test are passed, which proves the rationality and effectiveness of the design of composite insulator for bushing at UHV level. In this paper, starting from the typical electric field distribution characteristics of all kinds of composite insulators for bushing, the flashover law is studied for the first time, and the flashover test is carried out in the laboratory to supplement the classical test data. The research results have good theoretical and practical significance for installation, design and operation maintenance of all kinds of composite insulators.

2. UHV air gap flashover test and quantitative correction of composite insulator

2.1. Flashover test of UHV air gap
Firstly, the flashover test of UHVDC air gap is carried out. In the experiment, the maximum diameter of grading ring is 2893mm and the diameter is 350mm. In the test, the insulating structure grading ring is used to simulate the bushing grading ring, as shown in Fig. 1 (a). The grading ring has diameter of 2500m and pipe diameter of 220mm[9]. In the test, the grounding tower frame is used to simulate the grounding wall, as shown in Fig. 1 (b). The length of the tower frame is 18m, the width is 10m, and the bottom of the tower frame is 6m above the ground.
Figure 1  The Air gap test arrangement

(a) Grading ring  (b) Simulation wall

Figure 2  Layout of test site

\[ F(E; \alpha, \beta) = 1 - \exp\left\{-\left(\frac{E}{\alpha}\right)^\beta\right\} = 0.5 \]  

(1)

Figure 3  Test results on-site
The test object is arranged to simulate the actual operation scene of DC through wall bushing, and the axial direction of grading ring is 50° suspended above the ground, the arrangement of UHV air gap flashover test objects is shown in Figure 2. Two parameter Weibull distribution function is used to analyze the breakdown test data. According to the Weibull probability statistics theory, the flashover probability of air gap under UHV voltage is shown in formula (1). Where: $E$ - breakdown field strength / kV · mm$^{-1}$; $\alpha$ - Breakdown field strength at 50% breakdown probability, scale parameter / kV · mm$^{-1}$; $\beta$ - Shape parameters. According to the size and position of grading ring, the pressure test is carried out 12.6m away from the wall and 12.9m away from the ground. The meteorological conditions during the experiment are as follows: temperature $T = 5^\circ$C, relative humidity $R = 45\%$, air pressure $P = 101.7$KPa. Before the test, the meteorological correction of 2100kV switching impulse withstand voltage is carried out, and the correction result is 2094kV. The results of withstand voltage test are shown in Figure 3. The 20 data points are basically linearly distributed in Weibull coordinates. The slight dispersion of the line just shows the reliability of test results[10]. Take 50% flashover voltage, about 2105kV. The data points of 50% flashover voltage are relatively dense, which shows that it is reasonable to take 50% flashover probability as the actual flashover voltage value. The calculation results of 10.5m away from the wall and 12m away from the ground are shown in Figure 4.

2.2. Flashover test of hollow composite insulator for UHV bushing
Flashover test is conducted on the hollow composite insulator for the UHV bushing under laboratory conditions, and its arrangement is shown in Fig. 5(a). The capacitor core is installed inside the hollow composite insulator, the high voltage is applied to the grading ring at the end of the bushing, and the tail of the bushing is immersed in the transformer oil to simulate the actual operation environment. Fig. 5(b) shows that under the action of power frequency voltage, the initial flashover discharge occurs in the grading ring at the end of the bushing[11]. When the flashover occurs, the applied voltage value is automatically recorded.
In fact, the operating impulse withstand test voltage is mainly evaluated in the insulation structure size design of the hollow composite insulator. Considering that the flashover of the operating impulse dry withstand voltage and positive operating impulse wet withstand voltage occurs along the shortest path, the insulation level and insulation distance of bushing above 550kV are compared as shown in Table 1.

Table 1 shows that the ratio coefficient of 800kV bushing in Yuka station is 0.22, which is between 0.20 of 1100kV bushing in Southeast Shanxi and 0.24 of 1100kV bushing in Wuhan base. Therefore, from the perspective of field application, the bushing has good safety margin. On the other hand, according to the UHV air gap flashover test data, the quantitative fitting relationship between flashover voltage and insulation distance of composite insulator in air under four conditions of full wave lightning impulse dry/wet flashover voltage, positive operation wave dry/wet flashover voltage, power frequency dry flashover voltage (effective value) and power frequency wet flashover voltage (effective value) can be obtained quantitatively[12,13]. The quantitative relationship curve is shown in Fig. 6, and the nonlinear fitting is carried out by using the formula, where $U_{f50}$ is the flashover voltage value (discharge probability is 50%)/kV. $L_0$ is the dry flashover distance of insulator/m. $A$ and $B$ are undetermined coefficients. Therefore, the specific values of constants $A$ and $B$ are shown in Table 2.

### Table 1  Comparison of insulation level and insulation distance of bushing

| Parameters                        | minimum 550kV bushing | Routine 800kV bushing | Southeast Shanxi 1100kV bushing | Wuhan base 1100kV bushing | Yuka station 800kV bushing |
|-----------------------------------|------------------------|-----------------------|---------------------------------|---------------------------|---------------------------|
| Operation shock /kVpeak           | 1300                   | 1760                  | 1950                            | 1800                      | 1860                      |
| Insulation distance /m            | 4040                   | 6935                  | 9630                            | 7600                      | 8500                      |
| Ratio coefficient                 | 0.32                   | 0.25                  | 0.20                            | 0.24                      | 0.22                      |
Figure 6 The relationship between flash-over voltage and insulation distance of hollow composite insulator

Table 2 Quantitative relationship between flash-over voltage and insulation distance of composite insulator

| Type of test voltage                        | A   | B    |
|--------------------------------------------|-----|------|
| Lightning full wave impulse dry / wet flashover voltage | 545.5 | 0.9377 |
| Positive operating wave dry / wet flashover voltage | 603.4 | 0.6624 |
| Power frequency dry flashover voltage (RMS)   | 404.6 | 0.7053 |
| Power frequency wet flashover voltage (RMS)   | 372.3 | 0.6921 |

External insulation design verification: according to the requirements of dry arc distance greater than 7400mm and external insulation level of Yuka station, the dry flashover distance of 800kV bushing in the station is $L_g = 8500$mm. Calculation results of electrical performance of external insulation:

The power frequency dry flash $U_g$ is 1830.4kVr. M.S $> 1150$kVr. M.S, and the margin is 1.59.

The power frequency wet flash $U_s$ is 1637.4kVr. M.S $> 1150$kVr. M.S, and the margin is 1.43.

The lightning full wave impulse is 4058 kVpeak $> 2860$ kVpeak, and the margin is 1.42.

The operating impulse wet withstand voltage is 2490.3kVpeak $> 1860$kVpeak, and the margin is 1.34. According to the above calculation, when the insulation distance of upper porcelain part is 8500 mm, the power frequency withstand voltage, full wave impulse withstand voltage and switching impulse withstand voltage are all higher than the required voltage value, which can meet the engineering requirements for the electrical performance of external insulation of bushing [14,15]. The altitude correction factor $K$ is calculated according to formula (2).

$$K = e^{\frac{q(H-1000)}{8150}}$$

In equation (2), $H$ is the altitude/m. For lightning impulse voltage, the withstand voltage coefficient $q = 1$, and for air gap and bushing hollow composite insulator, the short-time power frequency withstand voltage $q = 1$. The altitude of the high altitude substation is $H = 3500$m, and the correction coefficient of switching impulse test voltage is $k = 1.36$, the correction value of power frequency test voltage is 960x1.36=1305kV, the correction value of the lightning impulse test voltage is 2100x1.36=2855kVpeak, and the correction value of switching impulse test voltage is 1550x1.26=1950kVpeak. It can be seen that it has high design margin for high altitude application environment[16,17]. The outline of outer porcelain sleeve of reactor bushing at high altitude is shown in Figure 7.
Figure 7 The outline of the outer porcelain of reactor bushing

Table 3 Comparative analysis of electrical performance, mechanical performance and applied bushing

| Parameter name | Routine 800kV bushing | Southeast Shanxi 1100kV bushing | Wuhan base 1100kV bushing | Yuka station 800kV bushing |
|----------------|------------------------|---------------------------------|--------------------------|---------------------------|
| Rated voltage $U_r$ kV | 800 | 1100 | 1100 | 800 |
| Rated current $I_N$ A | 2500 | 2500 | 2000 | 2500 |
| Switching impulse wet withstand voltage kVp | 1760 | 1950 | 1800 | 1950 |
| Lightning impulse withstand voltage kVp | 2550 | 2400 | 2400 | 2855 |
| Power frequency withstand voltage kV_{r.m.s} | 1020 | 1200 | 1200 | 1305 |
| Partial discharge under $U_r$ pC | < 10 | < 10 | < 10 | < 10 |
| Dielectric loss factor tanδ | $\leq 0.4$ | $\leq 0.4$ | $\leq 0.4$ | $\leq 0.4$ |
| Bending load N | 5000 | 11000 | 5000 | 5000 |
| Height of porcelain in oil mm | 1270 | 1830 | 1550 | 1270 |
| Insulation height of air terminal mm | 6930 | 9630 | 7600 | 9630 |
| Creepage distance mm | 24000 | 33000 | 27000 | 33000 |
| Installation with inclination of 30 degree seismic grade | VIII | VIII | VIII | VIII |
| The maximum stress of porcelain parts in the earthquake of VIII MPa (The horizontal acceleration is 0.3g) | 21 | 26 | 23 | 25 |
| Allowable stress of porcelain parts MPa | 60 | 60 | 60 | 60 |
| Total weight of bushing kg | 4480 | 6700 | 6500 | 5100 |


According to the comparative analysis of the electrical and mechanical properties of the designed bushing in Table 3, it can be seen that the rated voltage $U_r=800kV$ of the 800kV bushing in Yuka station is in the middle level, the rated current $I_N=2500A$ is in the high level, and its operating impulse wet withstand voltage is 1950kV, lightning impulse withstand voltage is 2855kV and power frequency withstand voltage is 1305kV, which are higher than the other three kinds of bushing. Partial discharge and dielectric loss factor $\tan\delta$ under $U_r$ meet the control requirements. At the same time, a good design margin is maintained in terms of mechanical properties. The maximum stress of porcelain parts is designed to be 23Mpa, the allowable stress of porcelain parts is designed to be 60MPa, the total weight of casing is designed to be 4900kg, and the bending load is designed to be 5000N. A good design margin is considered in the above designs.

3. Conclusion

a) Calculation results of electrical performance of external insulation: The power frequency dry flash $U_g$ is 1830.4kVr. M.S>1150kVr. M.S, and the margin is 1.59. The power frequency wet flash $U_s$ is 1637.4kVr. M.S>1150kVr. M.S, and the margin is 1.43. The lightning full wave impulse is 4058 kVpeak>2860 kVpeak, and the margin is 1.42. The operating impulse wet withstand voltage is 2490.3kVpeak > 1860kVpeak, and the margin is 1.34.

b) The partial discharge and dielectric loss factor $\tan\delta$ under $U_r$ meet the control requirements. At the same time, a good design margin is maintained in terms of mechanical properties. The maximum stress of porcelain parts is designed to be 23Mpa, the allowable stress of porcelain parts is designed to be 60MPa, the total weight of casing is designed to be 4900kg, and the bending load is designed to be 5000N. Good design margin is considered in the above designs.

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