Study on Structure Type and Operation Condition of UHVDC Wall Bushing

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Abstract. When the ±800kV UHVDC capacity is increased to 10000MW, the transmission current is 5kA and 6.25kA, which will put forward new requirements for the key technology of UHVDC through wall bushing: in UHV level, the key of through wall bushing lies in the research of basic technology of voltage sharing and field sharing. In the case of large current carrying capacity, the key lies in the basic technology research of current sharing and heat sharing. When the DC wall bushing, converter bushing and outgoing line device operate at the rated voltage, the central conductor is heated due to the carrying large DC current. Therefore, the temperature field distribution inside and at the tail of the bushing core is uneven, and the resistivity is the function of temperature, resulting in the change of resistivity with temperature and the change of potential and electric field distribution with resistivity during operation. Therefore, under the above high current operation conditions, in-depth key technology research is required for the design of bushing current carrying device, calculation of internal potential and electric field distribution, voltage sharing, field sharing, current sharing and heat sharing technology. The combined action of electrical and thermal stress will significantly affect the internal electric field distribution of converter transformer core and accelerate the aging rate of core composite insulation material, which introduces new research topic for the key technology of UHVDC converter bushing. The electric field and voltage distribution of UHVDC bushing are theoretically analyzed, the insulation structure is optimized from the aspects of material and structure, and the manufacturing process and the test technology are deeply and systematically studied.

1. Introduction
The development of ±1100kV UHVDC transmission technology can further improve the economic transmission distance and transmission capacity of DC transmission, effectively promote the efficient transmission of ultra long distance and ultra large capacity of thermal power, renewable energy, future hydro-power, international and even intercontinental energy in Northwest China, and promote intensive development and resource-saving of China's large energy bases on building an environment-friendly society[1-3]. China attaches great importance to research and development and engineering application of ±1100kV UHVDC transmission technology. Since organizing demonstration and determining ±1100kV as higher DC voltage level above ±800kV voltage. It has concentrated world's advantageous technical forces and resources to carry out the technology research and development and equipment development[4]. Wall bushing is a key equipment that can withstand 1100kV full voltage and current. It is very difficult and challenging to develop. It approaches or exceeds the limit of insulation, machinery and temperature rise technology. It is the key equipment that restricts the feasibility of the ±1100kV transmission technology and engineering construction[5-7]. In order to
understand the design requirements and operating conditions of ±1100kV DC wall bushing and the acceptance of relevant operating units for the V-shaped structure wall bushing proposed by the project team in the early stage, the project team went to ±800kV DC Fengxian converter station for investigation. Combined with investigation, the horizontal layout and V-shaped structure wall bushing were compared and analyzed.

2. Service conditions of 1100kV DC wall bushing
The ±1100kV DC transmission project planned in China is a bipolar DC system. The system includes two complete monopole, the each end of the each complete monopole is composed of two 12 pulse converters with the equal voltage in series, and the converter transformer is the single-phase and two winding. Any pair of 12 pulse converters in each complete monopole out of operation will not affect the incomplete monopole operation of the remaining converters. The rated current of the system is 1100kV, the rated current is 4750A, and the rated transmission capacity is 10450MW. ±1100kV DC wall bushing is used for the Zhundong converter station and Chongqing converter station [8,9]. The main wiring diagram of the DC system is shown in Figure 1. The operating environmental parameters of the two places are shown in Table 1 and Table 2.

±1100kV DC SF6 gas insulated through wall bushing is an important power device connecting DC outdoor equipment and equipment in valve hall. The through wall sleeve is used for the high-voltage current carrying conductor to pass through the wall of the valve hall to play the role of insulation and support. UHVDC System has strict requirements on the height and diameter of bushing. In particular, the design of shielding structure in through wall bushing is the key link.

![Figure 1 ±1100kV UHVDC SF6 gas insulated through wall bushing](image-url)

The internal shielding structure can effectively modulate the radial and axial electric field distribution inside the bushing, and the external insulation plays the role of uniform voltage distribution. Therefore, the more accurate electric field calculation of the internal shielding structure of ±1100kV DC SF6 gas insulated through wall bushing and the optimization design of the internal shielding type and position can effectively improve the internal and external insulation performance of the bushing. At present, there are few reports on the calculation and optimization design of shielding electric field in ±1000kV DC SF6 gas insulated through wall bushing[10-12]. Especially for UHVDC bushing, the internal shielding structure optimized under lightning impulse needs to meet the operation requirements under DC voltage, especially the restrictions on electric field distribution under the condition of polarity reversal. Therefore, the design and electric field calculation of UHVDC wall bushing are challenging.

For ±1100kV pure SF6 gas structure DC through wall bushing, the electric field calculation focuses on the electric field strength on the surface of the shielding layer structure and the potential electric field distribution of the glass winding cylinder. The shielding layer structure inside through wall bushing is mainly used to improve the axial and radial field strength inside the bushing, and make the
potential distribution on the surface of the glass winding cylinder close to the ideal linear potential distribution. While improving the electric field distribution inside the bushing, the electric field strength on the surface of the shielding layer structure also needs special attention, especially the electric field strength at the straight part of the shielding layer structure and the flanging position, as well as the electric field concentration on the surface of the glass winding cylinder. By optimizing the structure of the internal shielding layer, the electric field intensity on the surface of the shielding layer can meet the control requirements, and the possible high field intensity area on the surface of the glass winding cylinder can be eliminated. For ±1000kV epoxy impregnated dry-type DC wall bushing, the key focus area of field strength is the radial and axial electric field distribution inside the bushing core[13,14]. As the number of electrode plates in the core is up to hundreds of layers, the electric field modulation effect on the overall potential of the bushing is better than that of the pure SF6 gas structure DC through wall bushing. The potential distribution on the surface of glass winding cylinder is closer to the ideal linear potential distribution. For ±1100kV UHVDC SF6 gas insulated through wall bushing, the internal structure of ±1100kV UHVDC SF6 gas insulated through wall bushing is shown in Figure 2.

![Figure 2 Internal structure of ±1100kV UHVDC SF6 gas insulated through wall bushing](image)

There is the close relationship between the insulation structure inside the ±1000kV DC wall bushing and the insulation performance outside the bushing: the total length of the bushing must first meet the requirements of the creepage distance determined according to the pollution level. Based on the determination of the total length of the bushing, the full model electric field is checked and calculated in combination with the insulation in the bushing, and the inner diameter of the glass winding cylinder is determined according to the electric field calculation results. At the same time, it shall ensure that the surface field strength of the glass winding cylinder meets the control requirements and eliminate the occurrence of the external flash-over of the bushing. Conversely, under the operating conditions of pollution accumulation, icing and uneven rain, the electric field distribution in the bushing will also be affected to certain extent due to the obvious change of material conductivity. Therefore, in the early stage of bushing design, it is necessary to comprehensively consider, calculate and analyze the internal and external insulation of the bushing, and determine the reasonable and feasible internal shielding and external insulation structure.
Tab. 1 Environmental condition parameters of converter station of Zhundong Chongqing ±1100kV DC transmission project

| Serial number | Name                     | Unit        | Zhundong converter station | Chongqing converter station |
|---------------|--------------------------|-------------|----------------------------|-----------------------------|
| 1             | Ambient temperature requirements | ℃           | +41.2                      | +44.1                      |
|               | Maximum temperature      |             | -42.6                      | -25                        |
| 2             | Minimum temperature      |             |                             |                             |
| 3             | Altitude                 | m           | <1000                      | <1000                      |
| 4             | Solar radiation intensity | w/cm²       | 0.1                        | 0.1                        |
| 5             | Pollution level          |             | III                        | III                        |
| 6             | Icing thickness          | mm          | 10                         | 10                         |
| 7             | Wind speed               | m/s/Pa      | 34                         | 26                         |
| 8             | Annual average relative humidity | %           | ≦ 61                      | ≦ 83                      |
| 9             | Earthquake intensity     | m/s²        | 0.2g                       | 0.2g                       |

One end of the wall bushing is installed in the outdoor field and the other end is installed in the valve hall[15]. The internal environmental conditions of the valve hall are as follows: (1) Fully enclosed indoor, micro positive pressure, with ventilation and air conditioning; (2) Maximum temperature + 55 ℃; (3) Minimum temperature +10℃; (4) The maximum humidity 60% RH; (5) The specific creepage distance: 14mm/kV. The main wiring diagram of DC system is shown in Figure 3.

Figure 3 Main wiring diagram of DC system

3. Technical parameter requirements

The rated voltage of DC wall bushing is 1100kV, and the maximum DC voltage is 1122kV. Other rated parameters are shown in Table 2.

Tab. 2 Other rated parameters of converter station of Zhundong Chongqing ±1100kV DC transmission project

| Installation position | 1100kV | 550kV | Neutral |
|-----------------------|--------|-------|---------|
| Zhundong/Chongqing    | 5078   | 5078  | Zhundong Chongqing 5078 |
| Continuous DC current(Adc) | 5078 | 5078  | 5078    | 5078   |
| 2-hour overload current (Adc) | 5367 | 5367 | 5367 | 5367 |
|------------------------------|------|------|------|------|
| Short time withstand current 1s | 16   | 16   | 16   | 16   |
| Short time withstand current test (kApeak) | 40 | 40 | 40 | 40 |
| Maximum continuous DC voltage, to ground U_max (kVdc) | 1122 | 560 | 150 | 40 |
| Maximum voltage U_m of equipment relative to ground (kVrms) | 794 | 396 | 107 | 29 |

Tanδ, C Measure voltage, partial discharge test:

| Level | 1 test voltage (kVrms) | 396 | 198 | 54 | 15 |
|-------|------------------------|-----|-----|----|----|
| Level 2 test voltage (kVrms) | 832 | 416 | 113 | 32 |
| Level 3 test voltage (kVrms) | 1190 | 595 | 161 | 44 |
| Lightning impulse test voltage (kVpeak) | 2300 | 1300 | 550 | 550 |
| Operating impulse test voltage (kVpeak) | 2100 | 1175 | 503 | 503 |
| Power frequency 1min test voltage (kVrms) (dry) | 1096 | 620 | 264 | 264 |
| Power frequency 1h test voltage (kVrms) (wet) | 1190 | 595 | 161 | 44 |
| DC 2h test (kVdc) + partial discharge | 1683 | 840 | 225 | 60 |
| DC polarity reversal test (kVdc) + partial discharge (90/90/45min) | -1400/+1400/-1400 | -700/+700/-700 | N.A. | N.A. |
| DC wet withstand voltage (kVdc) | 1400 | 700 | 182 | 182 |
| Test voltage for radio interference test, end to ground (kVrms) | 794 | 396 | N.A. | N.A. |
| Minimum creepage distance: | | | | |
| outdoor (mm/kV) | 43 | 43 | 48 | 48 |
| indoor (mm/kV) | 14 | 14 | 14 | 14 |

Tab. 3 Harmonic current of through wall bushing

| Harmonic number r | A_rms |
|-------------------|-------|
| 2                 | 435   |
| 6                 | 35    |
| 12                | 50    |
| 24                | 15    |
| 42                | 100   |

The tensile force of bushing terminal shall not be less than: (1) Horizontal and longitudinal 2000N; (2) Horizontal and transverse 1500N; (3) 1000N in vertical direction; (4) The terminal shall be able to withstand at least 400N·m torque without deformation. The multi-objective optimization based on
electric field homogenization is shown in Figure 4. It shown the equi-potential distribution under the actual operating parameters and the convergence process of the multi-objective optimization.

4. Scheme design of the 1100kV UHVDC through wall bushing

The horizontal installation scheme is the conventional scheme, which has been widely used in the ±500kV and ±800kV converter stations, and some operation experience has been obtained. Generally, the UHVDC through wall bushing is not completely installed horizontally, but at an angle of 10° to the horizontal line, which is conducive to the internal heat dissipation of the bushing even if it is installed[16,17]. Figure 5 shows the overall dimension and installation diagram of ±800kV DC wall bushing in converter station.
use SF6 as the main insulation medium, and the insulation support cylinder or rod designed and manufactured by special materials will be used everywhere. The double-layer metal shielding or three-layer metal shielding structure will be adopted to solve the problem of axial and radial electric field distribution. In terms of thermal field distribution, solid conductive tubes, multiple heat dissipation devices and advanced heat conduction materials are adopted to solve the problem of product heat transfer. The V-shaped layout design scheme is the same as the horizontal layout scheme in terms of main insulation medium, external insulation selection, metal shielding and heat dissipation design. In terms of layout, the outlet bushing of inclined vertical structure is adopted inside and outside the valve hall, the GIS bus connection structure is adopted in the middle, and the special basin insulator is introduced to design three independent air chambers. Due to the segmented connection, the length of the internal conductive rod in the V-shaped layout design scheme can be shortened to 15000m at most. The design scheme is shown in Figure 6.

Figure 6 V-shaped layout design scheme of ±1100kV DC wall bushing

5. Comparative analysis of bushing structure types
From the dimensions of the above two design schemes, the total length of the bushing in horizontal arrangement scheme is 26m, and the total length of V-shaped arrangement in horizontal direction is about 25m. Therefore, from the perspective of horizontal space occupation, there is no substantive difference between the two. However, the V-shaped layout also needs to occupy space in the vertical direction, which will have certain impact on the layout of operation maintenance and other equipment. More importantly, since the bushing is inclined, in order to ensure the safe distance between the equipment, the equipment that can be directly placed under the through wall bushing needs to be arranged away from the high-voltage end of the bushing, which will inevitably increase the land occupation of the whole valve hall and outdoor field, and the distribution of electric field in the valve hall will also change. Referring to the layout of the ±400kV DC wall bushing of converter station after entering valve hall, the layout comparison of the two installation methods is preliminarily proposed, as shown in Figure 7. It can be seen that the use of V-shaped wall bushing will increase the floor area of the valve hall to certain extent.
In the horizontal arrangement, the length of the internal conductive rod will also reach 25000m and the weight is expected to reach 1000kg, so it is difficult to process and manufacture the conductive rod. At the same time, due to the long length and the heavy weight of the conductive rod, there will be certain deflection deformation after it is installed inside the bushing. Therefore, it is necessary to design an insulating support in the bushing to control the deflection deformation and ensure the concentricity between the guide rod, the insulating jacket and the metal shield, so as to meet the requirements of electric field distribution.

6. Conclusion
Through this investigation, the engineering application environment and technical parameters of ±1100kV through wall bushing are defined, and the horizontal layout scheme and V-shaped scheme are compared and analyzed. The conclusions are as follows:

a) The through wall bushing with V-shaped scheme will increase the floor area of the valve hall, and may pose an obstacle to the pedestrian or vehicle passage during operation and maintenance, which is not convenient for operation and maintenance.

b) The horizontally arranged ±1100kV wall bushing has the technical problems such as difficult manufacturing of guide rod, difficult deflection deformation control and poor mechanical performance, but these problems can be solved through the design breakthrough or improvement of manufacturing equipment. For V-shaped through wall bushing, the guide rod is short and the mechanical performance is good.

c) As there is no precedent for the application of V-shaped DC wall bushing, the user's acceptance of V-shaped scheme is low. The converter station is the earliest converter station built. Its equipment and design are foreign technology, and the DC wall bushing is oil immersed bushing.

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