Design and test of a 10 kV HV brushing for triaxial HTS cable termination

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Abstract. The high voltage (HV) bushing design of insulation core, umbrella skirt, lead type, and production process were proposed according to the technical requirements of the 10 kV high temperature superconducting (HTS) cable system of Shenzhen Power Supply Bureau. The design took full consideration of the withstanding voltage, impulse voltage, partial discharge, thermal shock, and anti-condensation level. According to the proposed design, a verification prototype was built and tested. It subjected to five slow 77 K-300 K thermal shock cycles and five severe 77 K-300 K thermal shock cycles to verify its performance. The sensitive electrical quantities were tested after each cycle. After the 10 cycles, no degradation of performance and no breakdown or flashover occurred were found in the prototype. The results show that the design is qualified for the expected purpose.

1. Introduction

High temperature superconducting (HTS) cable enables massive power transmission with little power loss under low voltage. In the last two decades, several HTS cable demonstration projects have been launched and several cable types, for example single core, 3-in-1, and triaxial type, have been proved suitable for some specific scenarios. Especially, triaxial HTS cable, whose three phases are concentrically wound on one former, has many advantages such as compact dimension, no electromagnetic emission, and smaller cost[1-3].

The high voltage (HV) bushing in the cable termination is one of the most important accessories of the HTS cable system, which acts as transition of temperature from cryogenic to ambient, of pressure from high pressure to atmosphere[4, 5]. The design of HV bushing need consider cryogenic and pressure seal, large operation temperature range, and anti-condensation. Furthermore, the bushing’s design voltage of triaxial termination should set as the line voltage for insulation test.

This paper introduces the design of HV bushing for triaxial HTS cable system. Withstanding voltage, thermal shock, low-temperature and high-pressure seal, and anti-condensation are all considered. Based on the design, we made a prototype and conducted tests. The results show that the design is reasonable and credible.
2. Bushing Design

2.1. General technical requirements

The HV bushings will be used in the Shenzhen triaxial HTS cable demonstration project, which was launched in 2017. According to the parameters of the project, the main external technical conditions of the HV bushing are listed as Table 1.

Table 1. Main design requirements of the HV bushing.

| No. | Parameter                | Requirement       |
|-----|--------------------------|-------------------|
| 1   | Rated voltage            | 6 kVrms           |
| 2   | Rate current             | 2.5 kArms         |
| 3   | tanδ                      | <0.5%             |
| 4   | Test voltage of withstand | 26 kV@30 min      |
| 5   | Test voltage of Impulse   | ±75 kV×10 times   |
| 6   | Partial discharge        | ≤10 pC@18 kV      |
| 7   | Working temperature      | 70 K-350 K        |

2.2. Bushing insulation core design

The insulation core adopts dry type, whose main components are epoxy, glass fibre, and capacitive screen. The innermost screen is equipotential with the current lead by physical connection while the outermost screen is equipotential with the flange (=ground potential). The equipotential inner screen forms a shield to the current lead so that no discharge will occur even if the copper lead is slightly defective. The length of the core below the flange is determined by the worst conditions of the insulation medium (i.e. cold nitrogen gas) while the length above is determined by the lightning voltage. The total length thus was 800 mm and below the flange is 400 mm. The insulation thickness is 16 mm and 6 capacitive screens were used taking into account the withstand voltage and lightning impulse test requirements. To match the cross-section of the current lead, the aperture of φ60 mm was determined, resulting in an external dimension of 92 mm.

2.3. Umbrella skirt design

Composite insulator, which is free of cleaning, less maintenance, and light weight, has excellent resistance to dirt flash, rain flash, and ice flash. It is a comprehensive cost-effective technical solution. The lightning test requirement is 75 kV of positive and negative polarity for 10 times, which is greater than the general 10 kV case. To improve the design margin, the arc distance is 295 mm, corresponding to 6 umbrella skirts. Since the above section is easy to appear condensation, which will deteriorate the insulation, alternating large and small umbrellas were used to avoid the formation of water flow.

2.4. Current lead interface design

The interface type of the current lead at the upper end is one of the most important issues in bushing design. The key points include electrical connection, cryogenic sealing, and easiness of installation. One type is the so-called "general's cap", which has two connection surfaces and uses face seal. The other is to make the lead directly feed through the end of the cap and use axial seal. This method has small contact resistance and allows a large current-carrying capacity, but axial seal is not easy to install. We decide to use the general’s cap type.

Figure 1. Current lead interface. (left): general’s cap; (right): feed-through
3. Tests and results

3.1. Test systems setup

Based on the design, we build a prototype and conduct HV tests as shown in Figure 2. The significant difference between the bushing used for HTS cable termination and the conventional one is the large operating temperature difference along the insulation core. So, the thermal shock test is the key item.

![Figure 2. HV test set-up for the bushing prototype](image)

We performed 5 slow thermal shock cycles, in which the HV bushing was slowly immersed into liquid nitrogen (LN2) cryostat (LN2 level of the cryostat was about 150 mm below the flange) for 15 minutes. Then it was taken out of the LN2 and brought to ambient temperature with the aid of an extractor fan. Then we performed 5 severe thermal shock cycles, in which the bushing was rapidly immersed into LN2 for 15 minutes cooling and taken out then insert into water pool at room temperature, as shown in the figure 3.

![Figure 3. (left): warm up slowly; (right): cool down and warm up rapidly](image)

The electrical properties of the bushing were measured after each cycle. The measurements included capacitance, tanδ, insulation resistance, and partial discharge at 26 kV. After the first, the fifth, and the tenth cycles, the tests of withstand voltage 26 kV for 30 min and standard lightning voltage ±75 kV for 10 times were conducted.

3.2. Results and Discussion

The results show that the performance of the designed HV bushing for triaxial HTS cable is stable under thermal shock cycles and there are no significant changes in the capacitance, tanδ, partial discharge (the system sensitivity is 5 pC) and other sensitive physical quantities. No breakdown or flashover occurs in the withstand voltage and lightning impulse and no abnormal sound is heard. When cooled in LN2, the umbrella skirt and current lead interface of the bushing shows obvious condensation. However, under these conditions, no breakdown or flashover occurs during lightning impulse tests.

| Item               | First cycle | Fifth cycle | Tenth cycle |
|--------------------|-------------|-------------|-------------|
| Capacitance/pF     | 764.0       | 769.6       | 767.8       |
| tanδ/%             | 0.423       | 0.418       | 0.429       |
| PD @ 26 kV/pC      | 3.0         | 3.1         | 3.8         |
4. Conclusion
According to the special technical requirements of HV bushing used in the triaxial HTS cable termination, such as working pressure, partial discharge, operation temperature range, condensation, etc., we proposed a dry type bushings design with full consideration of the insulation core, umbrella skirt, and current lead interface. A verification prototype was manufactured based on the design. The prototype was subjected to severely thermal shock cycles in the tests. The results show that the prototype has passed all the tests and reached the design expectation. The proposed design can be used for triaxial HTS cable system in the demonstration project.

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