Insulation design of ±10kV bipolar coaxial HTS DC cable

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Abstract. The high-temperature superconducting cable has low loss and high current-carrying density, and has extensive research prospects in power system transmission. In recent years, the advantages of DC transmission over long distances have become more and more obvious, and superconducting DC transmission has also become a research hotspot. Bipolar coaxial DC cable has a good economy, compact structure, and greater transmission power density, but also requires higher insulation, so the insulation design is particularly important. In this paper, a 10 kV / 6000 A / 10 m bipolar coaxial superconducting DC cable with a cold insulation structure is considered. In consideration of DC withstand voltage and lightning shock, an insulation design is carried out and a type test is performed. The test results meet the cable insulation requirements.

1. Introduction

The HTS cable has the characteristics of low loss and high carrier density and has a wide application prospect in power transmission. In recent years, there have been many demonstration projects at home and abroad. In traditional power grids, AC transmission is the most mature and economical transmission method, so the first superconducting cable is an AC cable. However, in recent years, the advantages of DC transmission in long-distance transmission have become more and more obvious. Applying superconducting cables to DC transmission can further reduce losses, reduce costs, and reduce volume. It comes to be a trend that using HTS DC cables in power transmission. Combining DC and HTS cables for high-power capacity transmission over long distances (to connect isolated RES units with centrally located load centers) have been proposed as the “Supergrid” concept a few years back[1].

Considering the different insulation structure of superconducting cable, it can be classified into low-temperature insulated and room temperature insulated cables. In low-temperature insulated cable, the superconducting layer and the insulating layer are both in a low-temperature environment. The low-temperature insulation medium plays the role of composite insulation. Low-temperature insulated cables have larger transmission capacity, smaller transmission loss, and lower operating costs. Especially, since the discovery of HTS, the cooling costs have been significantly reduced, so the application prospects of low-temperature insulated cables are more extensive.

DC cables can be divided into unipolar cables and bipolar coaxial cables according to the polarity of the conductor layer. The unipolar cable conductor layer transmits current in a single phase, and the bipolar coaxial cable transmits current in both directions. In 2011, a 10 kV / 2 kA / 200 m superconducting cable from CASER in Japan was a DC cable [2]. In 2012, the Chinese Academy of
Sciences designed a 1.3 kV / 10 kA / 360 m DC cable using unipolar power transmission \[3\]. This is the first HTS DC cable for industrial applications around the world. In 2014, a 80 kV / 3.25 kA / 500 m DC cable in Korea is connected to the grid, which uses a unipolar transmission method\[4\]. In 2015, Japan's 80 kV / 3.13 kA / 500 m DC cable used a bipolar coaxial transmission method\[5\]. Russia developed a 20 kV / 2.5 kA / 2500 m DC cable and installed it in the St. Petersburg power grid\[6\].

Compared with the unipolar type, the outer conductor layer of the bipolar coaxial cable can shield the magnetic field, optimize the magnetic field distribution between the inner and outer conductor layer, improve the critical current of the strip, and increase the current margin of the cable. Therefore, it has a good economy, compact structure, higher transmission power density, and higher insulation requirements. Insulation design is an essential and important part of HTS cables. It is mainly used for electrical insulation of superconducting materials, and also plays a role in cooling, anti-corrosion, moisture-proof, mechanical support, fixation and protection of superconductors. The failure of low-temperature insulation in the superconducting system is one of the main causes of quenching.

A 750 V/5000 A/260 m DC cable will be designed and installed in Tongli, Jiangsu province, which adopts a bipolar coaxial structure. In this paper, a 10 kV/6000 A/10 m bipolar coaxial superconducting structure DC cable is designed for type test of subsequent projects. In this paper, the main insulation structure of the test cable is designed, PPLP is selected for insulation, and the withstand voltage test is carried out. The result shows that the insulation structure meets the basic requirements.

2. Insulation design

The structure of bipolar coaxial DC cable is shown in figure 1. It is mainly composed of bellows skeleton, inner and outer superconductor layer, semi-conductive layer, the insulating layer, low-temperature channel, and protective cover. Considering transmission capacity, operation characteristics and design cost, low-temperature insulation structures are selected in this paper.

![Figure 1. The structure of bipolar coaxial DC cable](image)

2.1. Insulation material selection

There are many reasons for the failure of low-temperature insulation. Normally, HTS cables are produced at room temperature, and they are subjected to great electromagnetic force when working at low temperatures. In addition, in the process of cold and hot circulation, the cable insulation material is prone to slight deformation. On the one hand, if the insulation material does not have enough strength and suitable elongation, brittle cracking is easy to occur at low temperatures. On the other hand, if the thermal expansion coefficient of each part of the system vary widely, when the temperature changes, the interface of each layer of material will produce the stress caused by thermal shrinkage. When the stress is too large, the insulation material will be separated from the superconductor in the process of cold and hot circulation, resulting in insulation failure. Therefore, the choice of insulating material, the form, and effect of insulating material have a great influence on the performance of electrified conductor.

The requirements of HTS cables for insulating materials are: dielectric properties, low dielectric constant, dielectric loss, and sufficiently high dielectric strength, mechanical properties, which requires sufficient tensile strength and elasticity of the insulating material modulus and appropriate elongation in order to reduce the duty cycle, thermal performance, which requires the thermal expansion coefficient of the insulating material to match the other parts of the high-temperature
superconducting cable system. For the inner layer of the conductor, the insulation requires good dynamic thermomechanical properties, thermal stability, and thermal conductivity in order to facilitate cooling. And the outer layer insulation material needs good thermal insulation.

In the current-conducting conductor of the HTS cable, the inner and outer superconducting layers must withstand a voltage of 20 kV between them, and the skeleton bellows and the outer shield of the cable are grounded. These structures need to be insulated. Because the entire cable is in a liquid nitrogen environment, it must be compatible with liquid nitrogen and low temperature resistant electrical insulation materials, usually low-temperature insulation materials.

Polypropylene Laminated Paper (PPLP) is a kind of insulating paper developed by Japan's Sumitomo Electric Co., Ltd. It's a kind of insulating paper made of porous pulp material and polypropylene film. It has a three-layer structure, two outer layers are wood fiber paper, and the inner layer is polypropylene. The material cost of PPLP is lower than PI, and it has good impregnation performance, good mechanical properties and high electrical strength at low temperatures.

2.2. Calculation of insulation layer thickness

In this study, the insulation design of a bipolar coaxial high-temperature superconducting DC cable was performed based on the insulation design method of AC cables and national standards. In order to ensure the long-term stable and reliable transmission of high-voltage DC cables, DC working voltage and lightning surge voltage should be considered when designing high-voltage DC cables. According to national standard GB / T12706.2-2008 “Rated Voltage 1 kV (U_m=1.2 kV) to 35 kV (U_m=40.5 kV) Extruded Insulated Power Cables and Accessories Part 2: Rated Voltage 6 kV (U_m=7.2 kV) to 30 kV (U_m=36 kV) Cable”. The requirements of withstand voltage level of the insulation of 10 kV bipolar Coaxial high-temperature superconducting DC cables are shown in Table 1.

Table 1. ±10 kV bipolar coaxial DC cable insulation level requirements

| Test projects | Where voltage applied | Voltage level | Voltage application time or number |
|---------------|-----------------------|---------------|-----------------------------------|
| DC voltage experiment | Internal / external insulation | 35 kV | 5 min |
| | Main insulation | 70 kV | |
| Lightning impulse voltage experiment | Internal / external insulation | 75 kV | 10 times |
| | Main insulation | 125 kV | |

The deformation of the equation for the electric field strength generated by the coaxial cylindrical conductor can be obtained by equation (1)\(^7\),

\[
t_{dc} = r_0[(\exp\left(m_1 E_{dc}/r_0 U_{dc}\right)-1)]
\]

(1)

In equation (1), \(r_0\) is the radius of the cable core at the time of the initial winding of the insulation; \(U_{dc}\) for the DC withstand voltage, 35 kV of internal and external insulation is required, and the main insulation 70 kV, \(E_{dc}\) is the DC breakdown strength of the insulating material. The DC breakdown strength of PPLP in liquid nitrogen was obtained by fitting the experimental data, which is about 75kV / mm; \(m_1\) is a DC design margin and it can be calculated by equation (2)

\[
m_1 = K_1 K_2 K_3
\]

(2)
In equation (2), $K_1$, representing the DC aging coefficient, which can be calculated from the type test requirements, is about 1.35. $K_2$ is the temperature coefficient. For conventional cables, long-term running at room temperature will increase the heating temperature and cause the performance of the insulating material to deteriorate. However, for a superconducting cable with a cold insulation structure, the insulation layer works in a low-temperature environment, and there is no problem with the thermal aging of the insulation layer. Therefore, the temperature coefficient is set to be 1. $K_3$ is the safety factor, it’s set to 1.2.

The expression of the thickness of the insulation layer in the case of lightning shock is shown in equation (3):

$$t_{imp} = r_0\left[\exp\left(\frac{m_2 U_{imp}}{r_0 E_{imp}}\right) - 1\right]$$  \(3\)

The form of the equation is basically the same as the one under the DC condition. In this equation $U_{imp}$ is lightning impulse withstand voltage. It requires the internal and external insulation of 75 kV and the main insulation of 125 kV is required. $E_{imp}$ is lightning impact breakdown strength of insulating materials. The lightning impact breakdown strength of PPLP in liquid nitrogen is obtained by fitting experimental data, which is approximately 68 kV / mm. $m_2$ is design margin for lightning shock, which can be calculated by equation (4)

$$m_2 = K_4 K_2 K_3$$  \(4\)

where $K_4$ is the lightning shock aging coefficient, it’s set to 1.

Table 2. The thickness of the insulating layer at the required voltage level

| Insulation position               | DC voltage requirement | Lightning impulse voltage requirements | design result |
|----------------------------------|------------------------|----------------------------------------|---------------|
| Internal insulation thickness/mm | 0.77                   | 1.37                                   | 2.00          |
| Main insulation thickness/mm     | 1.56                   | 2.31                                   | 3.00          |
| External insulation thickness/mm | 0.76                   | 1.35                                   | 2.00          |

3. Test and result

3.1. Design of test sample

±10 kV / 6000 A low-temperature insulated superconducting DC cable, the outer diameter of the conducting conductor is φ66mm. The diameter of the cable skeleton, namely the liquid nitrogen flow pipe, is φ39mm. The length of the cable is 10m. The parameters and specific winding parameters of the multilayer structure are shown in Table 3. Each of the inner and outer superconducting layers has 100 superconducting tapes, which are wound in 4 layers. Each layer of PPLP insulation material is 0.12 mm thick. The main insulation layer is approximately 3 mm thick. And the inner and outer insulation layers are approximately 2 mm thick, with a 1 mm gap wrapping. The wrapping of the insulating layer is shown in figure 2.

Table 3. Parameters of the HTS DC cable

| Parameter                | Value(mm) | Texture          |
|--------------------------|-----------|------------------|
| Inner insulation         | 2         | PPLP             |
| Inner superconducting layer | 2       | Superconducting tape |
| Main insulation          | 3         | PPLP             |
| Outer superconducting layer | 2       | Superconducting tape |
| Outer insulation         | 2         | PPLP             |
3.2. **Insulation withstand voltage test**

A complete superconducting dc cable system is formed by placing an energized conductor into a low-temperature Dewar and connecting it with two terminals. The effective length of the HTS dc cable in the middle section is 7.5m, the sample length between the outer conductors at both ends is 9.6m, and the sample length between the inner conductors at both ends is 11.7m.

The sample for the cable insulation resistance test is in the first place. According to the “GB/T 3048.5 2007 Electrical Wire and Cable Test Methods Part 5: Insulation Resistance Testing”, the resistance was tested respectively at room temperature and liquid nitrogen temperature. They are the resistance between the inner conductor and the outer metal shielding layer, or between the outer conductor and the outer metal shielding layer or between the inner and outer conductor. The test voltage is 250 V.

The test site is shown in the figure, and the test results are shown in table 4.

**Table 4. Results of the insulation resistance test**

| The environment temperature (274 K) | Liquid nitrogen temperature (77 K) |
|-------------------------------------|----------------------------------|
| The resistance between the inner conductor and the metal shielding layer | The resistance between the outer conductor and the metal shielding layer | The resistance between the inner conductor and the metal shielding layer | The resistance between the outer conductor and the metal shielding layer | The resistance between the inner and outer conductor |
| $1.85 \times 10^4 \, \text{M}\Omega$ | $1.57 \times 10^4 \, \text{M}\Omega$ | $2.62 \times 10^6 \, \text{M}\Omega$ | $3.44 \times 10^4 \, \text{M}\Omega$ | $1.26 \times 10^4 \, \text{M}\Omega$ | $1.67 \times 10^6 \, \text{M}\Omega$ |
According to “GB/T 3048.14-2007 Test Methods for Electrical Performance of Wires and Cables Part 14: DC Voltage Test”, DC voltage test was conducted. The bellows were connected to the metal-connected ground potential, the inner conductor applied -40kv voltage, and the outer conductor applied + 40kv voltage. The voltage continued for 5 min without a breakdown of the sample.

The DC voltage superposition lightning impulse voltage test method shall be conducted in accordance with “GB/T 31489.1-2015 extruded insulated power cable system for DC transmission with rated voltage up to and including 500 kV”. The test is divided into positive and negative polarity lightning shock test. The bellows are connected to the metal grounding potential, and the rated DC voltage of 10kV is applied to the inner and outer conductors. A lightning surge voltage is applied to the outer conductor, which has the opposite polarity to the DC voltage of the outer conductor. The samples were not broken down after 10 positive and negative lightning shocks. The results show that the sample cable meets the requirements of cable insulation.

### Table 5. Positive polarity dc voltage superimposed negative polarity lightning impulse voltage

| Specified voltage for superimposed lightning impulse test: 21 kV | Applied DC voltage | Actual withstand impulse voltage |
|---------------------------------------------------------------|--------------------|---------------------------------|
| DC voltage | Lightning impulse voltage | Grounding | kV | kV |
| Voltage applied to | polarity | Voltage applied to | polarity | Metal shield | |
| Inner conductor | Negative | Outer conductor | Negative | 10 | 20.9 20.6 |
| Outer conductor | Positive | | | 10 | 20.9 21.3 |
| | | | | | 21.1 |
| | | | | | 21.1 21.0 |
| | | | | | 21.2 21.3 |
| | | | | | 21.2 |

### Table 6. Negative polarity dc voltage superimposed negative polarity lightning impulse voltage

| Specified voltage for superimposed lightning impulse test: 21 kV | Applied DC voltage | Actual withstand impulse voltage |
|---------------------------------------------------------------|--------------------|---------------------------------|
| DC voltage | Lightning impulse voltage | Grounding | kV | kV |
| Voltage applied to | polarity | Voltage applied to | polarity | Metal shield | |
| Inner conductor | Positive | Outer conductor | Positive | 10 | 20.8 20.8 |
| Outer conductor | Negative | | | 10 | 21.7 21.9 |
| | | | | | 21.4 |
| | | | | | 21.5 21.3 |
| | | | | | 21.3 21.4 |
| | | | | | 21.4 |

4. Conclusion

In this paper, the insulation for a ±10 kV / 6000 A / 10 m bipolar coaxial cold-conducting superconducting DC cable is designed. The thickness of the cable insulation layer is calculated in consideration of DC withstand voltage and lightning impact, and a sample cable is prepared. The type test of the sample cable is carried out. Results show that the sample cable meets the insulation...
requirements and shows good insulation characteristics in the 10 m sample cable. It ensures the reliability of the high-temperature superconducting insulation design technology.

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