1. Introduction

With the continuous improvement of the power grid voltage level, the continuous expansion of the scale, and the rapid development of new energy, the power grid needs stronger security stability and reliability. Superconductivity can improve the security stability and power quality of power grid in transmission, current limiting, energy storage and other aspects[1-2]. Compared with traditional cables, high temperature superconducting (HTS) cables have higher current density, lower power loss, and smaller size. Various forms of HTS cables have applied around the world[3].

The breakdown characteristic of the insulation materials has been studied in some researches. Ombello studied the AC and lightning pulse breakdown properties of polypropylene laminated paper (PPLP), HDPE fiber and ethylene propylene rubber (EPR) in liquid nitrogen[4]. Rezaeifar studied the characterization of PPLP partial discharge in the HTS cable composite insulation system[5]. J. K. Seong systematically investigated the AC and DC breakdown characteristics of various cryogenic insulating films, including Kraft, Kapton, and Nomex[6]. A large number of experiments have shown that PPLP and Kapton thin films have good mechanical properties, low-temperature stability, and low-temperature dielectric strength. They are the preferred low-temperature insulating materials for superconducting power equipment and occupy the main position in the superconducting cable insulation.

The insulation performance of PPLP is very important when PPLP is chosen as the insulation layer of HTS cable. There have many researches on the insulation properties of PPLP, but few researches on the insulation properties of PPLP after heating. However, PPLP used for HTS cable has to endure a period of time during the copper joint welding, and the insulation performance of PPLP after heating directly affects the insulation performance of HTS.
In this paper, the insulation structure of HTS cable is introduced, and PPLP is selected as the insulation material of HTS cable. Due to the fact that the PPLP will be heated during copper joint welding, the insulation characteristics of the heated PPLP at different times are studied, and the AC breakdown experiment of the PPLP is conducted. By comparing the insulation characteristics with the original PPLP, the theoretical basis is provided for the insulation design of the HTS cable.

2. Thermo Gravimetric Analysis

2.1. Insulation structure of HTS cable

HTS cable can be divided into low-temperature dielectric insulated cable and room temperature dielectric insulated cable. Room temperature dielectric insulated cable has high loss and running cost, so low-temperature dielectric insulated cable is used in most of HTS cable systems. The lapping insulation is selected for the main insulation structure[7].

![Figure 1. Three-phase coaxial cable structure.](image)

In low-temperature lapping dielectric superconducting cable, liquid nitrogen is filled between the lapping layers. The electric field at the interface between liquid nitrogen and insulation layer is less abrupt, which effectively increases the initial voltage of partial discharge and the breakdown voltage. A three-phase coaxial cable structure is shown in Figure 1.

![Figure 2. Diagram of PPLP wrapping structure](image)

The superconducting cable is cooled by liquid nitrogen. Figure 2 is a schematic diagram of the PPLP lapping structure. PPLP is used as the insulation layer, and a 1-2 mm gap between the same layer can ensure that the cable has a certain bending radius.

2.2. DSC curve analysis of PPLP

In order to study the insulation characteristics of the heated PPLP, the thermo characteristics of the PPLP were firstly analyzed. The differential scanning calorimetry (DSC) curve of PPLP was measured. DSC is a technique for measuring the difference in heat flow between the input to sample and the reference sample, a function of heat flow with temperature and time using a programmed temperature method.
Figure 3. DSC curve of PPLP.

Figure 3 shows the DSC curve. According to the curve, the glass transition of PPLP occurs at 65.99°C, and the molecular chain changes from free motion state to non-free motion state. 164.30°C is the melting temperature of PPLP, after which the PPLP begins to crystallize and the orderly molecular chain is destroyed. The melting temperature of the insulation material affects its mechanical and insulating properties. Therefore, when welding copper head, should not exceed 164.30°C.

3. Experimental Analysis

In the process of making HTS superconducting cable, the copper joint needs to be weld for the cable.

Figure 4. Schematic diagram of copper head welding completion.

Figure 4 shows the copper head after welding. Since the copper joint is large, it is necessary to heat the copper joint first before welding, and it will take about 40 min to finish welding. Because of the heat conduction, the insulating material PPLP will also be heated. The melting temperature of the traditional solders used for welding is 138°C, 145°C and 183°C. Since 183°C exceeds the melting temperature of PPLP, it is not recommended to use. Considering the temperature distribution of the cooper current lead during the welding process, the PPLP is heated at 160°C in the worst case to observe its insulation performance.
The insulation performance of the heated PPLP is very important for the insulation design of the cable. The schematic diagram of the breakdown experiment is shown in Figure 5. PPLP needs to be heated before the experiment. The oven is used to heat the PPLP at 160 °C for 10 min, 20 min, 30 min, 1 h, and 2 h, respectively. After heating, the PPLP is tested for voltage breakdown.

Figure 5. Schematic diagram of breakdown experiment.

Power frequency breakdown is to apply processing frequency voltage to the sample by means of continuous and even boost, and keep the voltage value when the sample breakdown occurs. The experiment was conducted in the air, and the rising rate of voltage was set as 0.5 kV / ms. After a breakdown, samples were taken out and data were recorded.

Figure 6. Ф6 mm diameter electrode for measuring narrow strip.

Figure 6 shows the electrode for measuring the narrow strip, and the electrode diameter is 6 mm. Power frequency breakdown is to apply processing frequency voltage to the sample by means of continuous and even boost, and keep the voltage value when the sample breakdown occurs. The experiment was conducted in the air, and the rising rate of voltage was set as 0.5 kV / ms. After a breakdown, samples were taken out and data were recorded.

Figure 7. AC breakdown Weibull distribution of heated PPLP.

Figure 7 shows the AC breakdown Weibull Distribution of heated PPLP with different heating times. It can be seen that the AC breakdown voltages of heated PPLP follow Weibull Distribution.
Table 1 shows the AC breakdown field strength of PPLP corresponding to 0.1% Weibull Distribution probability. It shows that within 20 minutes of heating, the insulation of PPLP gradually degrades. With the increase of the heating time, the insulation performance fluctuates up and down but is always lower than that of unheated PPLP. Thus, the insulation thickness at the weld shall be increased.

Table 1. AC breakdown field strength of PPLP corresponding to 0.1% Weibull distribution probability.

| Dielectric strength kV/mm | 0 min | 10 min | 20 min | 30 min | 1 h | 2 h |
|---------------------------|-------|--------|--------|--------|-----|-----|

4. Conclusion

The insulation structure of HTS cable is introduced in this paper. Using PPLP as an insulating material, the DSC curve of PPLP was obtained through experiments, and the characteristics of PPLP were analyzed. The AC breakdown experiment of PPLP with different heating time was conducted at 160°C. It was found that within 20 minutes of heating, the insulation of PPLP gradually degrades. With the increase of the heating time, the insulation performance fluctuates up and down but is always lower than that of unheated PPLP.

References

[1] E. B. Forsyth, “The high voltage design of superconducting power transmission design”, IEEE Electrical Insulation Magazine, 1990, vol.6, no.4, pp. 7-16.
[2] K. Fossheim , Handbook on Superconducting Technology, World Scientific Publishing Co., PTE Ltd., Singapore, 1991, pp. 149-173.
[3] H. Thomas, A. Marian, A. Chervyakov, et al. "Superconducting transmission lines-Sustainable electric energy transfer with higher public acceptance?", Renewable and Sustainable Energy Reviews, 2016, vol. 55, pp. 59-72.
[4] F. Ombello, G. Attolini, P. Caracino, et al. "Insulating materials evaluation for cold dielectric superconducting cables", IEEE Transactions on Dielectrics and Electrical Insulation, 2003, vol.9, no.6, pp.958-963.
[5] Rezaeifar, Suzuki, Kumada, et al. "Characterization of partial discharge in composite insulation system with PPLP for HTS cable", IEEE Transactions on Dielectrics & Electrical Insulation, 2010, vol.17, no.6, pp. 1747-1753.
[6] J. K. Seong, I. J. Seo, J. S. Hwang, et al. "Comparative evaluation between DC and AC breakdown characteristic of dielectric insulating materials in liquid nitrogen", IEEE Transactions on Applied Superconductivity, 2012, vol. 22, no.3, Art. no.7701504.
[7] T. N. de Sousa, D. Kottonau, J. Bock, et al. "Investigation of a concentric three-phase HTS cable connected to an SFCL device", IEEE Transactions on Applied Superconductivity, 2018, vol.28, no.4, Art. no. 5400105.