Journal of the Korea Institute of Applied Superconductivity and Cryogenics
Vol.5, No.3, (2003), pp.43~47

The Effect of Butt Gap in Insulation Properties for a HTS Cable

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Abstract-- **For an electrical insulation design of HTS cable, it is important to understand the dielectric characteristics of insulation materials in LN_2 and the insulation type. Generally, the electrical insulation of HTS Cable is classified into two types of the composite insulation and solid insulation type.**

In this research, we selected the insulation paper/LN_2 composite insulation type for the electric insulation of a HTS cable, and studied electric insulation characteristics of synthetic Laminated Polypropylene Paper (LPP) in liquid nitrogen (LN_2) for the application to high temperature superconducting (HTS) cable. Furthermore, we compared the breakdown characteristics of the butt gap and bended mini-model cable. It is necessary to understand the winding parameter of insulation paper/LN_2 composite insulation.

1. INTRODUCTION

For an electrical insulation design of HTS cable, it is important to understand the dielectric characteristics of insulation materials in LN_2 and the insulation type. Generally, the electrical insulation of HTS Cable is classified into two types. One is composite insulation, made by dielectric papers and LN_2, which is similar to the dielectric structure of oil filled cables, while the other is solid insulation which is similar to that of XLPE cables [1]. As for composite insulation, contraction due to cooling down to LN_2 temperature can be absorbed readily because the insulation is composed of dielectric tapes wound spirally around a conductor. It is also important to reduce heat losses in the cable. For this reason, we selected composite insulation system for the insulation design of the HTS cable in Korea [2][3]. However, taped insulation system contains some butt gaps between insulating layers that can become the source of partial discharge [4][5]. It is very important to investigate the HTS cable insulation. Also, a HTS cable can classify a flexible type and a rigid type by flexibility. This research develops the HTS cable that is flexibility given to the cable core and former [2][6].

Therefore, in this paper, we researched breakdown characteristics of the butt gap in the LPP/LN_2 composite insulation system for application of a HTS cable. And, we studied the electric insulation characteristics of the bended mini-model cable in LN_2.

2. EXPERIMENT

2.1 Sheet Samples and Electrode System

The sheet samples are commercially available LPP that is made in Finland. LPP is consisted of two layers of Kraft paper with thickness of 25 ㎛ and rough polypropylene film with thickness of 69㎛. The technological cycle of fabrication of synthetic paper contains the thermal calendaring operation, so total thickness of LPP is 119 ㎛. The basic properties of tested LPP are given in table I.

TABLE I
THE BASIC PROPERTIES OF LPP

Density, g/cm^3	0.89
Tensile strength, kN/cm^2	
-Machine direction	7.42
-Cross direction	4.45
Polypropylene ratio, %	57
tanδ (100℃), %	0.055
Thickness, ㎛	120.8 (Normal: 119)

Figure 1 shows the sheet samples and electrode system for an electric breakdown test. A punch hole simulating a butt gap was placed at the four cases of the center. The experiments were conducted: a butt gap contacted with a high voltage electrode (upper hole); a butt gap not contacted with any electrode (middle hole); a butt gap contacted with a ground electrode (lower hole); and attaching without butt gap (no hole). In case of exist butt gap, the center of sample has been cut off in the shape of circular hole of diameter 6 mm artificially.

The sheet samples were used for the measurement of breakdown characteristics in LN_2. We used the polished stainless steel electrode to the high voltage conductor in the experiment. The electrodes used in the experiment are ϕ 40 mm and ϕ 60 mm plane electrodes respectively. The high voltage electrode is molded with epoxy resin to avoid the edge effect. Also, LPP used in the breakdown test has been not exceeding 0.1 % of moisture and dried around 105 ℃ ('NREL Standard Procedures #001' Measurement Method).

Figure 2 shows the schematic diagram and insulation composition of mini-model cable. This mini-model cable is manufactured by LPP for secure insulation data. This cable is wrapped with carbon paper on flexible SUS former serially starting from the first layer, then LPP is wrapped

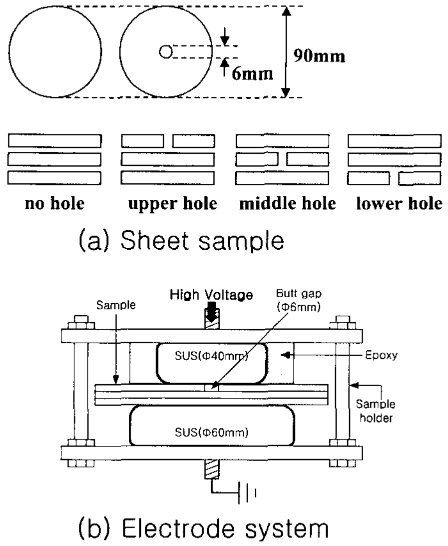

Fig. 1. Sheet samples and electrode system for test of hole arrangement.

that overlapped 30 % between each layers. The LPP cutting width is 25 mm, and butt gap size is 1 mm. The available length of mini-model cable is 300 mm, and total length is 1100 mm. And this mini-model cable has 1 mm of thickness. The stress cone made LPP to prevent surface flashover of cable terminal.

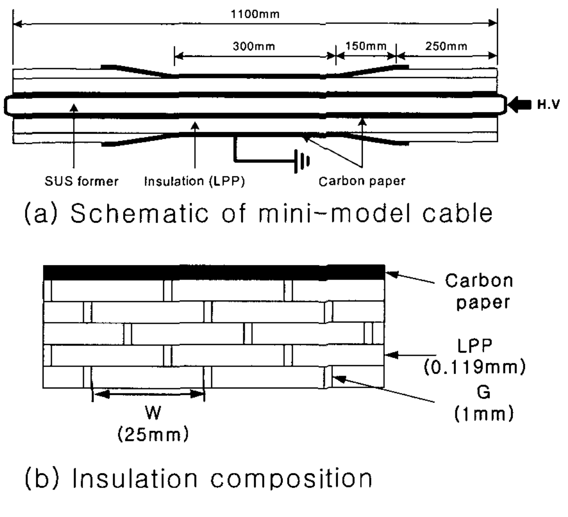

Fig. 2. Schematic diagram and insulation composition of mini-model cable.

Figure 3 shows the schematic diagram of the experimental apparatus. This SUS cryostat has duplex vacuum layers and can give stability of LN_2 thermally. Also, it is used to measure pressure properties under the pressure carried out applying 1~4 atmosphere. The capacity of the AC power supply is 60 Hz, 90 kV / 300 VA.

2.2. Sheet Samples and Electrode System

A step-rising AC voltage (60 Hz with the rise 1 kV/sec) was applied to the samples for the breakdown test. And the

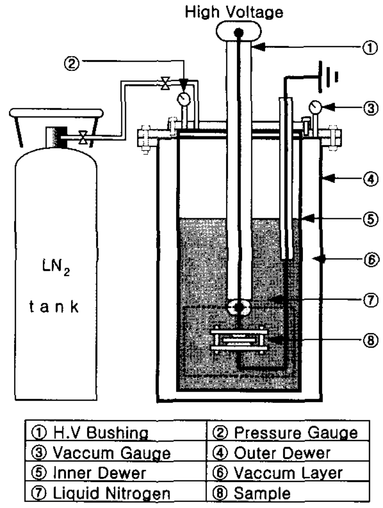

Fig. 3. Schematic diagram of the experimental apparatus setup.

Impulse voltage is applied by the Impulse apparatus (1.2 × 50 μs waveform, Maximum 300 kV). The partial discharge inception stress is measured using a partial discharge detector (IEC6027, Nihonkesoki Co.).

3. EXPERIMENTAL RESULT AND DISCUSSION

3.1 Breakdown Characteristics of the Sheet Samples with Butt gap

Figure 4 shows the test result of the AC breakdown voltage by hole of sheet samples with butt gap, which have various hole location. In samples with butt gap, the middle hole samples have a little higher breakdown voltage than others. In the upper hole samples and lower samples, they are considered that the breakdown voltage decrease because of activated partial discharges due to easy supply of the initial electron with the contact of the hole with the electrode. When sheet samples are deposited to LN_2, liquid and micro voids are existed in the butt gap. Because the permittivity of them is lower than that of LPP, the dielectric breakdown has happened easily. And the electrode that contact with hole emits electron fast more than others. Therefore, the dielectric breakdown voltage is lowest at the upper hole and lower hole.

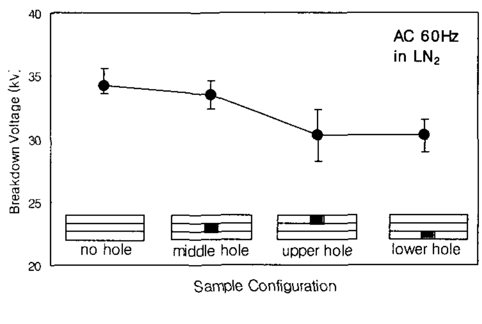

Fig. 4. AC breakdown voltage according to hole arrangement.

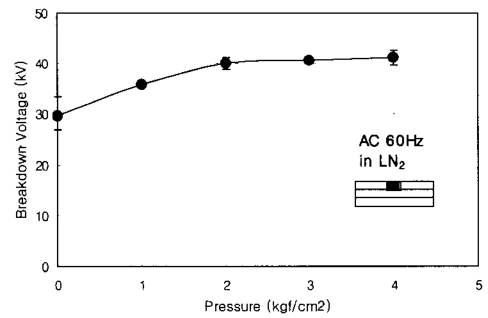

Fig. 5. AC breakdown voltage according to pressure in the sheet samples with upper hole.

Figure 5 shows the AC breakdown voltage according to the pressure in the sheet samples with upper hole. The breakdown voltage of this samples increased according to the increase of the pressure. And the breakdown voltage saturated at 2 kgf/cm^2 nearly according as pressure increases. This phenomenon is considered that the increase of pressure makes the increase of density. Therefore, 2 kgf/cm^2 is important to decide the operating pressure of a HTS cable.

Figure 6 shows the AC breakdown voltage by the variation of distance between butt gaps. And, figure 7 shows the breakdown channel by distance between butt gaps. This test is to decide the overlapping rate of insulation paper. Overlapping rate means degree that is piled up between two layers of the insulating papers. And it can find out the suitable distance between butt gaps. In figure 6, it shows that breakdown voltage increase according to increase of distance between butt gaps, and saturated. The breakdown channel in distance of less than 8 mm between butt gaps occurs the surface discharge as shown in figure 7 (a). It means that the breakdown channel is formed upper hole and finished in the middle hole. This phenomenon is not observed at room temperature, but only at cryogenic temperature. The discharge is apparently broken at impact with a solid dielectric at LN_2 temperature. The variety of electron mobility and the surface charge will be formed, and then the electric field is distorted. The dielectric strength of LPP is higher at cryogenic temperature than that of room temperature, so its surface maintains this impact and the discharge runs between

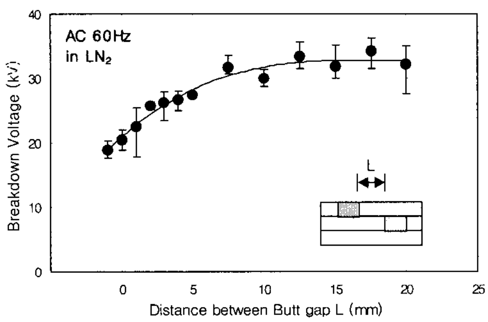

Fig. 6. AC breakdown voltage by the variation of distance between butt gaps.

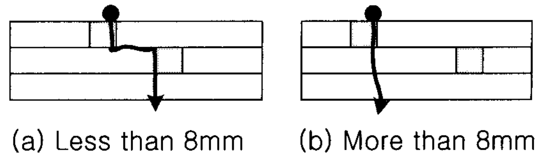

Fig. 7. Breakdown channel by the distance between butt gaps.

insulating layers.

Figure 8 shows the surface flashover discharge probability by distance between butt gaps. In case that distance is less than 2 mm, surface flashover discharge occurred all. However, the increase of distance between butt gaps reduces a probability of originating of the ramified breakdown channel. The breakdown was occurred through the insulating layers one by one from top to bottom as shown in figure 7 (b). This phenomenon is very important to decide the optimal distance between butt gaps, so more than 8 mm is recommendable as the suitable distance. Based on this result, the decided most suitable distance between butt gaps (L) is 8 mm and cutting width of LPP is 25 mm. Therefore, the most suitable overlapping rate was decided 30 % by follow equation (1).

$$Overlap(\%) = \left(\frac{L}{W}\right) \times 100 \quad (1)$$

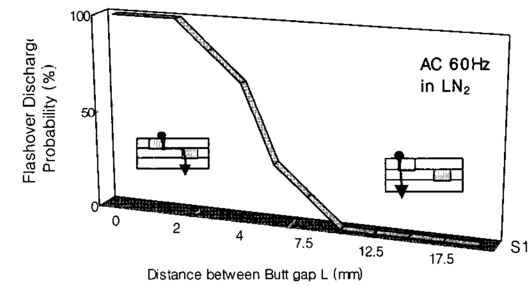

Fig. 8. Surface flashover discharge probability by distance between butt gaps.

3.1. Breakdown Characteristics of the Mini-model Cable

This research develops the HTS cable that is flexibility given to cable core and former. Therefore, we studied the electric insulation characteristics of the bended mini-model cable.

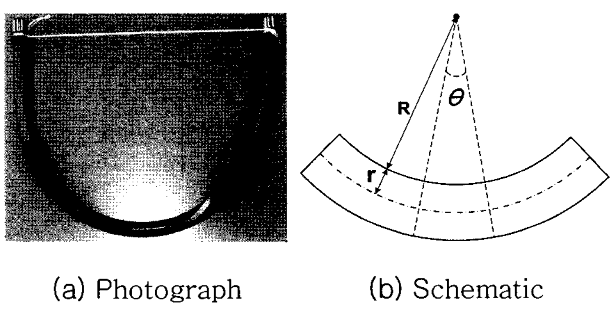

Fig. 9. Photograph and schematic diagram of the bended mini-model cable.

Figure 9 shows the photograph and schematic diagram of the bended mini-model cable in order to decide the bending-radius ratio of a HTS cable. This mini-model cable is manufactured by overlapping rate of 30 %. In figure 9 (b), r is radius of cable (15 mm), R is bending radius of cable, and θ is bending angle. The bending-radius ratio R/r of the manufactured mini-model cable is five cases (R/r= 10, 15, 20, 25, straight).

Figure 10 shows the AC and Impulse breakdown voltage of mini-model cables for the bending radius ratio test. The Impulse breakdown voltage is higher than AC breakdown voltage, but the shapes of curve are very similar. In cases of the cable of straight and 25 times are having similar breakdown voltage almost, and decreasing sharply at R/r is 10 times. This phenomenon is considered that is because butt gap has more faults as a mechanical and tensile stress, and this is volume effect [7].

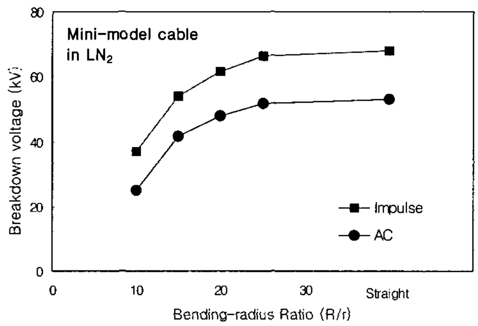

Fig. 10. AC and Impulse breakdown voltage of mini-model cables for the bending-radius ratio test.

Figure 11 shows the inception and extinction stress of partial discharge by the bending-radius ratio of mini-model cables. Also, the partial discharge characteristics indicate tendency similar to AC and Impulse breakdown characteristics. In this experiment, the LPP cutting width (W) of 25 mm and butt gap size (G) of 1 mm used for insulation of the mini-model cable. So, refer to figure 9 (b), the suitable bending-radius ratio R/r of cable can be explained by follow equations:

$$W + 2G = (R + 2r)\theta \tag{2}$$

$$W = R\theta \tag{3}$$

$$\frac{R}{r} = \frac{W}{G} \tag{4}$$

If the suitable bending-radius ratio using equation (4), it explain roughly 25 times. This is similar almost with previous actuality experiment result.

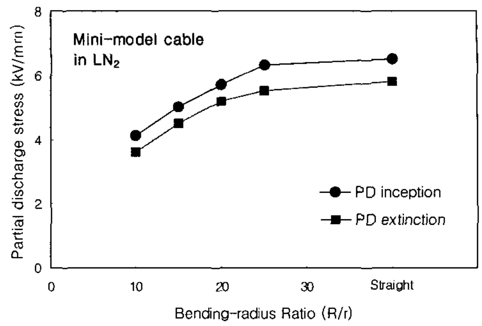

Fig. 11. Partial discharge by the bending-radius ratio of mini-model cables.

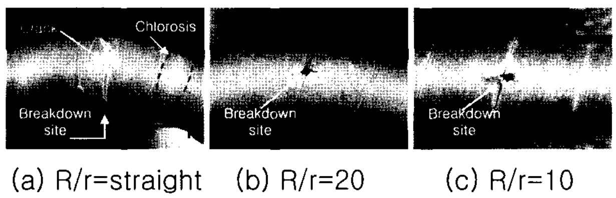

Fig. 12. Breakdown Site of the Bended Mini-model Cables.

Figure 12 shows the breakdown site of the bended mini-model cables. In case of the straight cable, butt gap is starting point of the electric discharge. Also, in case of R/r=20 times, the space of cable shows some Chlorosis (whitening of the surface), but the electric discharge started at butt gap. However, in case of R/r=10 times, the space of cable shows the serious Chlorosis and crack, and the electric discharge stated at crack. This is reason that the insulation property of cable become fall down sharply at the bending-radius ratio R/r is 10times.

4. CONCLUSION

We researched the insulation characteristics of the sheet samples with butt gap and the bended mini-model cable to decide the suitable bending-radius ratio of a HTS cable. In the experiment of sheet samples, the most suitable distance between butt gaps was decided length of 8 mm, and moreover, overlapping rate was decided 30 %. Base on these data, we manufactured the mini-model cable. And, the bending-radius ratio of the bended mini-model cable has five cases (R/r=10, 15, 20, 25, straight). In the AC, Impulse and partial discharge properties, all test results show the similar tendency, and the suitable bending-radius ratio R/r was decided more than 25 times.

ACKNOWLEDGMENT

This research was supported by a grant from Center for Applied Superconductivity Technology of the 21st Century Frontier R&D Program funded by the Ministry of Science and Technology, Republic of Korea.

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