고온 초전도 케이블의 절연설계를 위한 복합절연물의 시험 연구

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Experimental Investigation of Composite Insulator for Insulation Design of HTS Cable

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Abstract

Due to the outstanding insulating characteristics, Laminated Polypropylene paper (LPP) and Kraft paper have been used as ac power insulation for conventional cable. Recently, both of LPP and Kraft has been studied as main insulation for high temperature superconducting (HTS) cable. However, studies on the use of LPP/Kraft paper for HTS cables are thinly scattered. In this paper, the comparison among LPP, Kraft and LPP/Kraft samples impregnated with liquid nitrogen (LN_2) on dielectric insulation characteristics was investigated. It was found from the experimental data that the breakdown strength becomes lower in the order LPP, LPP/Kraft and Kraft but the lifetime indices *n* becomes lower in the order Kraft, LPP/Kraft, LPP. Moreover, partial discharge inception and dielectric loss tangent become lower in the order Kraft, LPP, LPP/Kraft.

Key Words : breakdown strength, dielectric insulation, HTS cable, liquid nitrogen, polypropylene.

1. Introduction

The high temperature superconducting (HTS) cable is anticipated to transport large electric power densities with a compact size due to high critical current density property of HTS conductor compared to that of conventional copper ones [1,2]. Laminated polypropylene paper (LPP) has been used as oil-filled power cable insulation to replace Kraft paper because of its lower dielectric loss and higher dielectric strength [3,4]. Recently, LPP has been being used as tape insulation for HTS power cable because it can be easily impregnated with liquid nitrogen (LN_2) and its dielectric loss is smaller than that of Kraft paper but nearly the same with oriented polypropylene laminated (OPPL). Moreover, the breakdown strength of LPP is higher than that of Kraft paper but its lifetime indices *n* is smaller than that of Kraft paper [5,6]. In Korea, in support to the 21st century frontier research and development project, the research on the use of LPP as tape insulation for HTS cable has been carried out [7,8]. Nevertheless, the comparison among LPP, Kraft and LPP/Kraft sample on dielectric insulation characteristics has not been investigated sufficiently. In this paper, the breakdown strength, V-t, partial discharge and dielectric loss tangent characteristics of LPP, Kraft and LPP/Kraft samples were studied in order to be able to find out the best insulation material for HTS cable.

2. Experimental Apparatus and Procedure

Two kinds of material insulation were used in this experiment; these are 0.12 mm thickness Kraft paper and 0.119 mm thickness LPP. Because of the highly hygroscopic nature of Kraft paper, vacuum drying of sample was done at a temperature of 100 oC for 24 h prior to testing [9]. In determining the breakdown strength characteristics of LPP and Kraft multi-layer, flat specimens with buttgap were used and the numbers of layers were varied from two to seven. In the case of studying the breakdown strength of LPP/Kraft multi-layer, we also used flat specimens with buttgap as shown in Fig. 1.

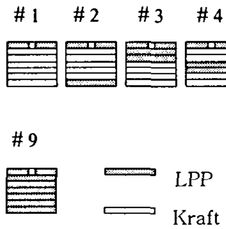

Fig. 1. LPP/Kraft specimens.

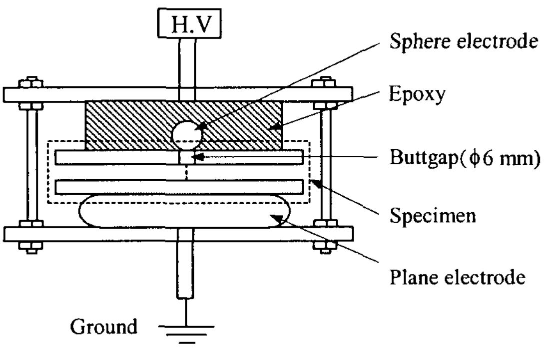

Fig. 2. Electrode configuration.

Fig. 2 shows the electrode configuration for breakdown strength experiment. The specimens were laminated between sphere and plane electrodes. The diameter of sphere and plane are 8 mm and 60 mm, respectively. The electrodes are made of stainless steel, and the sphere electrode was molded with epoxy resin to avoid partial discharge on the electrode surface.

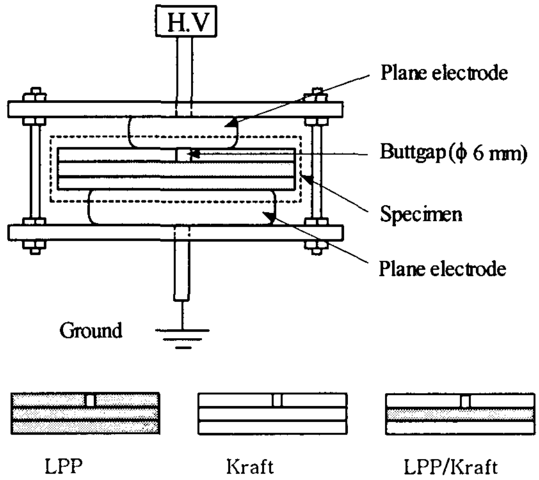

Fig. 3. Electrode system and specimens for PD and V-t.

Fig. 3 shows the flat specimens and flat electrode system for V-t and partial discharge (PD) experiment. The stainless steel flat electrodes have 40 mm and 60 mm in diameter.

Fig. 4 shows the electrode system for measurement of loss tangent with 1 mm thickness of multi-layer insulation of LPP, Kraft and LPP/Kraft.

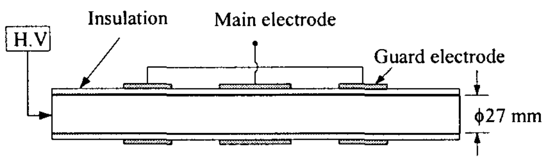

Fig. 4. Electrode system for loss tangent measurement.

The cryostat used in this study is shown in Fig. 5. The innermost dewar is filled with liquid nitrogen whish is also houses the electrode system. In order to keep the influence of the ambient temperature to a minimum, the test liquid was thermally isolated from the ambient by mean of vacuum and liquid nitrogen.

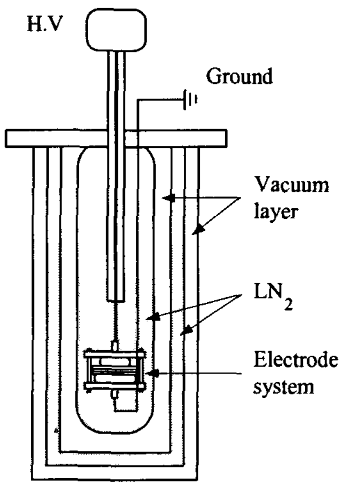

Fig. 5. Cryostat and experiment setup.

Ac breakdown test was carried out according to standard method. The test samples were subjected to a slow ac ramp (1 kV/s) one by one until breakdown occurred [10]. In case of impulse test, firstly, a voltage estimated to be 70 % of breakdown value, was applied to a test object. The voltage was then increased in steps of 4 kV until a breakdown occurred [11]. The polarity of applied impulse voltage was also changed. For both of ac and impulse test, the breakdown test was repeated 10 times for each sample to obtain an average value of breakdown voltage. In order to determine V-t characteristics, we first measured the breakdown strength and calculated 50 % cumulative probability of breakdown strength (BD_{50}) from Weibull plot and then measured the time to breakdown with the applied voltage in the range of 100 % to 85 % of BD_{50}.

3. Experiment results and discussions

3.1. Breakdown strength characteristics

The breakdown strength of LPP and Kraft as a function of thickness is shown in Fig. 6.

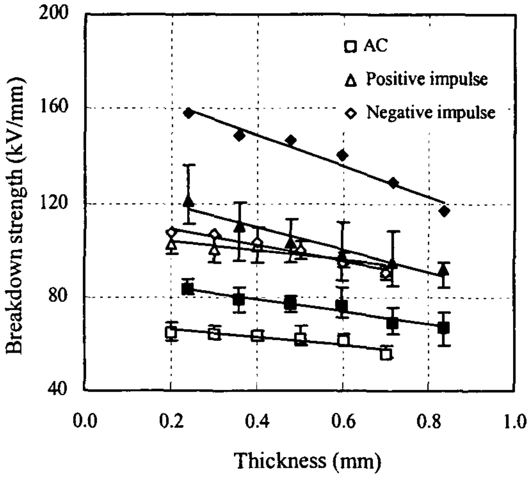

Fig. 6. Breakdown strength versus thickness. Full symbols for LPP; empty symbols for Kraft.

This figure shows that breakdown strength decreases linearly with increasing thickness. However, The breakdown strength and standard deviation of LPP are higher than those of Kraft. Moreover, in both cases, impulse breakdown strength is much higher than ac breakdown strength and its standard deviation is also larger than that of ac breakdown strength. In LPP case, the value of negative impulse is much higher than that of positive impulse, but the positive and negative breakdown strength are nearly the same in Kraft case. This is due to a formation of positive streamer and the positive charges are trapped on the surface of PP film while the positive and negative charges spread easily into Kraft paper [11]. From this result, it is inferred that the polarity of applied voltage has a strong effect to the breakdown strength of LPP and has a slightly effect to the breakdown strength of Kraft. In addition, the different value of breakdown strength between LPP and Kraft becomes smaller as the thickness increases and the breakdown strength line of LPP is steeper than that of Kraft, so the thickness of LPP has a significant effect on the breakdown strength characteristics as compared to Kraft paper.

Fig. 7 shows the breakdown strength characteristics of LPP/Kraft. It shows that ac breakdown strength of specimen 9 (LPP only) gets the highest value while specimen 1 (Kraft only) has the lowest value and the value of LPP/Kraft is between LPP and Kraft (see 2, 3, 4, 5, 6, 7, 8). In addition, the breakdown strength increases as the number of LPP in LPP/Kraft increases and fluctuates as the specimens with inserting place of LPP (see 3, 4, 5) changes. The positive impulse breakdown strength of LPP (9) is a little higher than that of Kraft paper (1) due to the effect of thickness. The value of LPP/Kraft specimen 5 gets the highest value in comparison with those of LPP specimen 9 and Kraft specimen 1. This is due to the effect of positive charges, which are trapped on the PP film [11]. In addition, the breakdown strength of LPP/Kraft greatly varies with the changing of number of LPP and relative position of LPP.

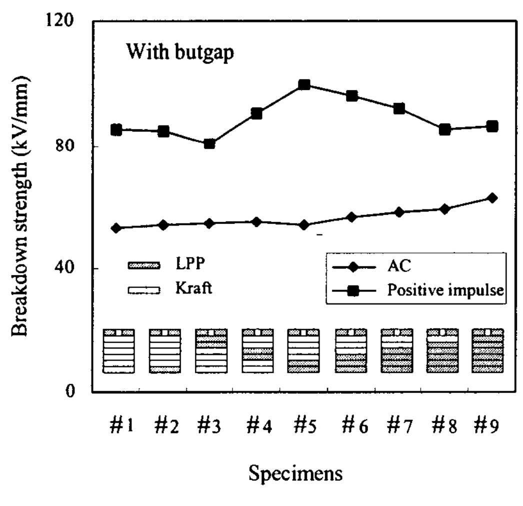

Fig. 7. Breakdown strength characteristics of LPP/Kraft.

3.2. V-t characteristics

V-t characteristics of LPP, Kraft and LPP/Kraft are shown in Fig. 8. The curves in this figure satisfy the so-called Inverse Power Law model of the following form

$$E^{n}t = const \qquad (1)$$

This figure indicates that the lifetime indices n becomes lower in the order Kraft, LPP/Kraft and LPP, so the slope of V-t characteristic becomes lower in the order LPP, LPP/Kraft and Kraft. This means that a small increase in electric stress causes dramatic decrease in lifetime of Kraft, so Kraft is more sensitive to over-voltage than LPP/Kraft and LPP. Conversely, LPP having low n value will show good resistance to over-voltage, but extrapolation to long lifetimes may yield an unacceptably low working stress. For these defects, LPP/Kraft becomes the best choice for long term working stress in comparing to LPP and Kraft.

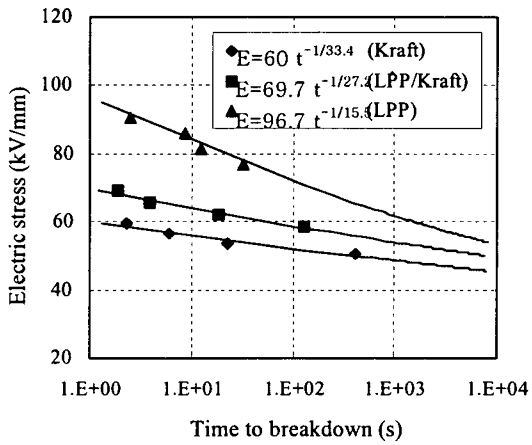

Fig. 8. V-t characteristics.

3.3. Partial discharge characteristics

Fig. 9 shows the partial discharge (PD) characteristics of LPP, LPP/Kraft and Kraft. The PD charge increases nonlinearly with increasing electric stress. At low electric stress, the PD charge is free but at high electric stress the PD charge increases sharply. PD inception of LPP/Kraft is lowest while the value of LPP and Kraft are almost equal. Nevertheless, Fig. 6 and Fig. 7 indicate that the ac breakdown strength becomes higher in the sequence Kraft, LPP/Kraft and LPP. These could conclude to verify that the corona-proof of LPP is higher than that of Kraft.

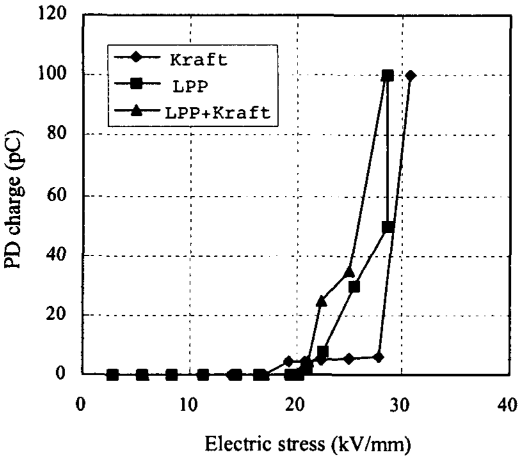

Fig. 9. Partial discharge versus electric stress.

3.4. Dielectric loss tangent characteristics

Fig. 10 depicts the tanδ as a function of electric stress. It can be observed that at first, the tan remains fairly constant and then increases very steeply with increasing the electric stress. The tanδ gets higher in the order of LPP/Kraft, LPP and Kraft, so LPP/Kraft achieves the lowest dielectric loss. The reason is that the component of Kraft is fiber, so Kraft acquires high dielectric loss. Reducing fiber component in Kraft will reduce dielectric loss, thus replacing Kraft with LPP will decrease the dielectric loss.

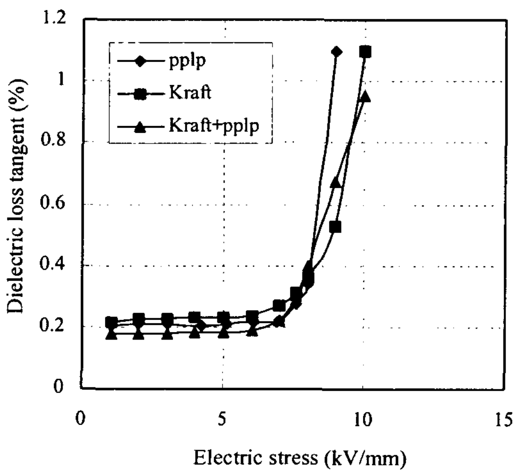

Fig. 10. Dielectric loss tangent versus electric stress.

4. Conclusions

Based on the results, the following conclusions can be drawn:

1) The ac breakdown strength becomes lower in the order LPP, LPP/Kraft and Kraft.

2) The impulse breakdown strength gets lower in the order LPP/Kraft, LPP and Kraft.

3) The lifetime indices *n* becomes lower in the sequence Kraft, LPP/Kraft and LPP.

4) The partial discharge inception and tanδ become lower in the order Kraft, LPP and LPP/Kraft.

With plain sample, LPP/Kraft promises to turn the best insulation for HTS cable but we must study more on tube sample and mini-model in order to conclude which material is the best insulation for HTS cable accurately.

Acknowledgment

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References

[1] A. Mansoldo, M. Nassi, and P. Ladie, HTS Cable Application Studies and Technical/Economical Comparisons with Conventional Technologies, presented at the IEEE Winter PES Meeting, 2002.

[2] D. Politano, M. Sjostrom, G. Schnyder, and J. Rhyner, Technical and Economical Assessment of HTS Cables, *IEEE Trans. Applied Superconductivity*, vol. 11, no. 1, pp. 24772480, March 2001.

[3] S. Minemura and Y. Maekawa, 500 kV Oil-Filled Cable Installed on Bridge, *IEEE Trans. Power Delivery*, vol. 5, no. 2, pp. 840-845, April 1990.

[4] Y. Watanabe, H. Fukagawa, Z. Iwata, and R. Hata, Development of new 500 kV Laminated

Paper Insulated Self-Contained Oil-Filled Cable and Its Accessories, *IEEE Trans. Power Delivery*, vol. 3, no. 1, pp.4762, 1988.

[5] A. Bulinski and J. Densley, High Voltage Insulation for Power Cables Utilizing High Temperature Superconductivity, *IEEE Electrical Insulation Magazine*, vol. 15, no. 2, pp. 1422, 1999.

[6] H. Suzuki, K. Ishihara and S. Akira, Dielectric Insulation Characteristics of Liquid-Nitrogen-Impregnated Laminated Paper-Insulated Cable, *IEEE Trans. Power Delivery*, vol. 7, no. 4, pp.16771680, 1992.

[7] M. Andreev, S. Y. Kim, I. H. Lee, D. W. Kim, and D. S. Shin, The Effect of Butt Gaps on Dielectric Strength of Taped Insulation in Superconducting Cable, *KIEE Journal of Applied Superconductivity and Cryogenics*, vol. 5, no. 1, pp.128132, May 2003.

[8] D. S. Kwag, Y. S. Kim, H. J. Kim, and S. H. Kim, The Effect of Butt Gap in Insulation Properties for a HTS Cable, *KIEE Journal of Applied Superconductivity and Cryogenics*, vol. 5, no. 3, pp.4347, Nov. 2003.

[9] Standard Method for Preparation and Electrical Testing of Insulating Paper and Board Impregnated with Liquid Dielectric, ASTM D2418, 1997.

[10] Standard Test Method for Dielectric Breakdown Voltage and Dielectric Strength of Solid Electrical Insulating Materials at Commercial Power Frequencies, ASTM D149, 1997.

[11]K. Saitoh, Y. Kawakami, and M. Murata, The Effect of The Polypropylene Film on The Impulse Breakdown Stremgth of The Laminated Oil-Impregnated Papers, in *Conf. Rec.* 1992 *IEEE Int. Symp. Electrical Insulation*, pp. 209212.