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Original Article

Breakdown Characteristics of Composite Insulation for High Temperature Superconducting Cable

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Abstract: Polypropylene laminated paper (PPLP) and Kraft paper have been studied as multi-layer insulation for high temperature superconducting cable. The experiment was conducted with AC and impulse voltages. Short-term and long-term breakdown of insulation samples were investigated. The experimental results show that the breakdown voltage becomes smaller in the order of PPLP, PPLP/Kraft and Kraft, but the lifetime index increases with the presence of Kraft layer in the multi-layer insulation. In addition, the position of PPLP layers has a significant effect on the breakdown voltage of PPLP/Kraft samples under positive impulse voltage. Finally, breakdown mechanism of PPLP/Kraft composite insulation was suggested. Partial discharges in butt-gaps and in the porous structure of insulation layers combined with electric discharges on the surface of these layers are considered to be main factors causing the puncture of multi-layer insulation.

Keywords: Breakdown voltage, lifetime, insulation, superconducting, cable

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]. Polypropylene laminated paper (PPLP) 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, PPLP has been used as insulation for HTS power cable because its dielectric loss is smaller than that of Kraft paper and nearly the same with oriented polypropylene laminated. In addition, the breakdown strength of PPLP was observed to be higher than that of Kraft paper, but its lifetime index is smaller than that of Kraft paper [5, 6]. The studies on the use of PPLP as

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tape insulation for HTS cable were carried out [7, 8]. Nevertheless, the comparison among PPLP, Kraft and PPLP/Kraft samples for both short-term and long-term breakdowns has not been investigated sufficiently. In this paper, the breakdown characteristics of PPLP, Kraft and PPLP/Kraft under both AC and impulse voltages were performed. In addition, *V-t* characteristics of these three kinds of insulation samples were examined with AC voltage.

2. Experiments

2.1. Materials

Two kinds of material insulation were used in this experiment. These are 0.12 mm thick Kraft paper and 0.119 mm thick PPLP, which consists of a PP film laminated by two layers of Kraft paper. Because of the highly hygroscopic nature of Kraft paper, vacuum drying of sample was performed at a temperature of 100°C for 24 h prior to testing [9]. For determination of the breakdown voltage of Kraft and PPLP multi-layer insulation, square specimens with butt-gap of 6 mm were used, and the number of layers was varied from two to seven (Figure 1a). In the case of studying the breakdown voltage of PPLP/Kraft multi-layer, the arrangement of specimens was shown in Figure 1b, and Figure 1c was used for *V-t* test of 1 and 3-layer samples.

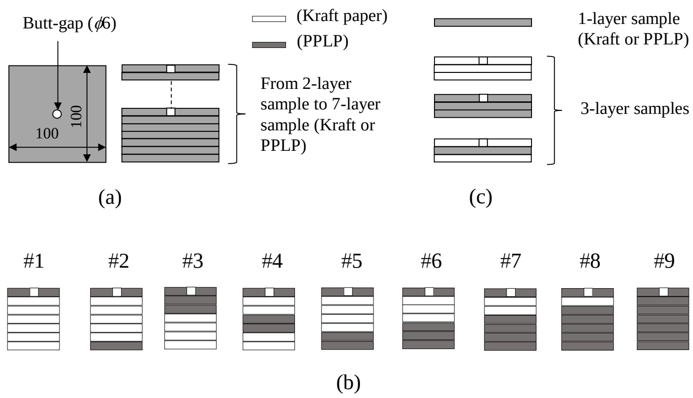


Figure 1. Insulation samples: (a) Kraft or PPLP, (b) PPLP/Kraft and (c) *V-t* test.

2.2. Experimental Setup

Figure 2a shows the electrode system for experiment. The specimens were laminated between sphere and plane electrodes. The diameter of sphere and plane are 8 mm and 60 mm, respectively. All electrodes are made of stainless steel, and the sphere electrode was molded with epoxy resin to avoid partial discharges on the electrode surface. The cryostat used in this study is shown in Figure 2b. The innermost Dewar is filled with liquid nitrogen in which the electrode system is immersed. In order to keep the influence of the ambient temperature to a minimum, the test liquid was thermally isolated from the ambient by means of vacuum and liquid nitrogen.

2.3. Experimental Procedure

AC breakdown test was carried out according to the ASTM D149, and the test samples were subjected to a slow AC ramp (1 kV/s) one by one until breakdown occurred [10]. In the 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. The polarity of applied impulse voltage was also changed. For both AC and impulse tests, the breakdown test was repeated 10 times for each type of samples. In order to determine *V-t* characteristics, we first measured the breakdown voltage and calculated 50 % cumulative probability of breakdown voltage (BDV_{50}) from Weibull plot, and then measured the time to breakdown with the applied voltage in the range of about 80 % to 100 % of BDV_{50}. The electrical test apparatuses were an AC dielectric strength test set, which is made by Kyonan Electric CO., LTD (50/60 Hz, 100 kV, 1 kVA) and an impulse voltage tester system produced by Dae Yang Electric CO., LTD (1.2 × 50 µs, 400 kV, 15 kJ).

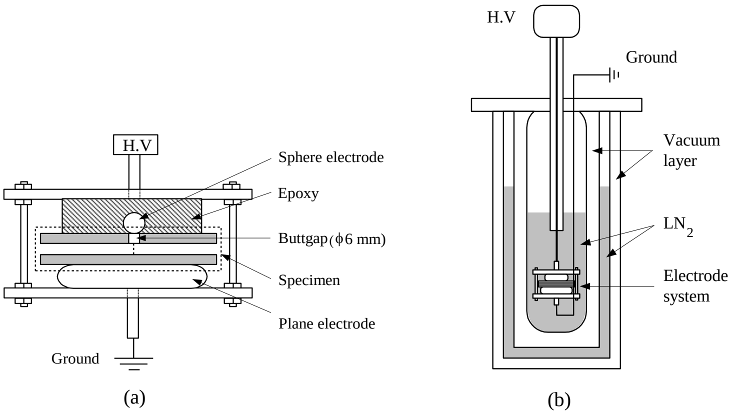


Figure 2. Experimental setup: (a) electrode system and (b) cryostat.

3. Results and Discussion

3.1. Breakdown Characteristics

3.1.1. Kraft Paper and PPLP

The correlation between the breakdown voltage and the number of Kraft layers is shown in Figure 3. The experimental results show that the breakdown voltage increases linearly with increasing layer numbers, i.e. thickness. Similar results were presented in references [5, 11]. For both positive and negative polarities, impulse breakdown voltage is about 2 times higher than AC breakdown voltage. However, there is no significant difference in breakdown voltage between positive and negative cases. Thus, the polarity of applied voltage has no effect on the breakdown voltage of Kraft paper. This is in line with what reported by other researchers [12]. The reason is that positive and negative charges associated with partial discharges in the butt-gaps spread easily into Kraft paper [13]. Similar to Kraft paper, the breakdown voltage of PPLP was observed to linearly rise with layer numbers, and impulse breakdown voltage is still much higher than AC breakdown voltage. Unlike Kraft paper case, the polarity of applied voltage has a strong effect on the breakdown voltage of PPLP. Negative impulse voltage is about 1.5 times higher than that of positive impulse voltage. This is due to the suggestion that positive charges resulted from partial discharges are trapped on the surface of PP film of PPLP samples, leading to an increment in local electric field and puncture PPLP layers at lower applied voltage [13]. Similar results were reported by other researchers [14]. Compared to Kraft paper, PPLP shows a significantly higher breakdown voltage under both AC and impulse voltages. This is in agreement with what reported in references [5, 6, 8, 11]. This result could confirm the fact that the corona-proof of PPLP is higher than that of Kraft paper. However, the shape parameter of Weibull plots is higher for the case of Kraft paper under both AC and impulse as shown in Figure 4 (30.15 and 29.01 compared to 25.99 and 27.15). This indicates that the breakdown data of PPLP scatter over a wider range than that of Kraft paper.

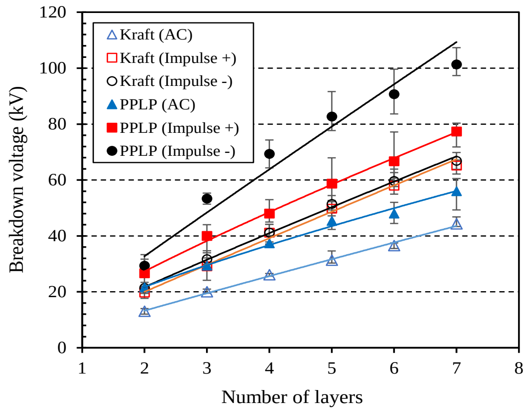
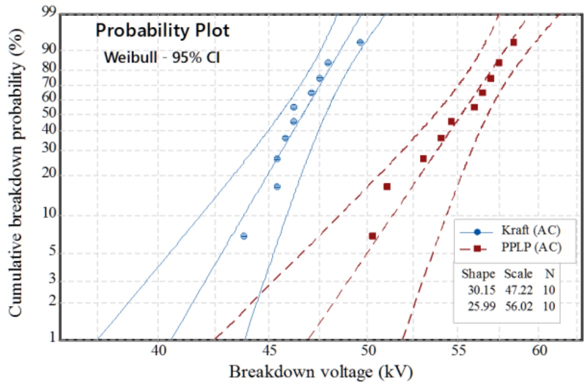
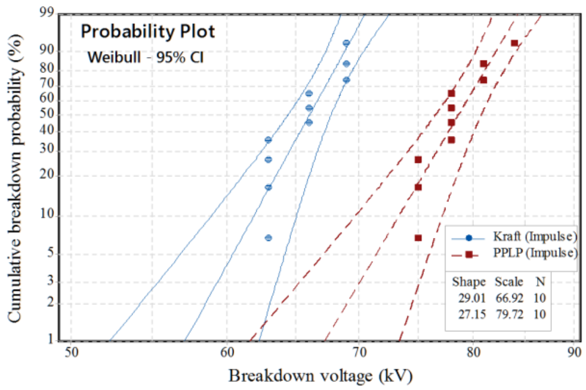


Figure 3. Breakdown voltage versus the number of layers of Kraft paper and PPLP.



(a)



(b)

Figure 4. Weibull plots of 7-layer samples: (a) AC voltage and (b) Positive impulse voltage.

3.1.2. PPLP/Kraft Paper

Figure 5 shows the breakdown voltage of PPLP/Kraft samples compared to those of Kraft paper and PPLP. It shows that AC breakdown voltage of PPLP (#9) reaches the maximum value while Kraft paper (#1) has the minimum value, and the breakdown voltage of composite insulation (PPLP/Kraft) is in between PPLP and Kraft cases (see #2, #3, #4, #5, #6, #7 and #8). The experimental results also show that the AC breakdown voltage is proportional to the number of PPLP in PPLP/Kraft samples and slightly varies with the sequence of PPLP layers in PPLP/Kraft samples (see #3, #4, #5). Like AC case, there is significant difference in positive impulse breakdown voltage between PPLP (#9) and Kraft paper (#1). The positive impulse breakdown voltage of PPLP/Kraft sample (#5) reaches the highest value compared to PPLP (#9) and Kraft paper (#1), and with the same number of PPLP layers, the positive impulse breakdown voltage becomes higher for samples in which PPLP layers are far from the positive electrode (see #3, #4, #5). Therefore, the impulse breakdown voltage of composite insulation (PPLP/Kraft) depends not only on the number of PPLP layers but also on the sequence of PPLP layers in PPLP/Kraft samples. This result is in agreement with what presented in references [11, 13]. This is due to the effect of positive charges that are trapped on the PP film of PPLP samples [13].

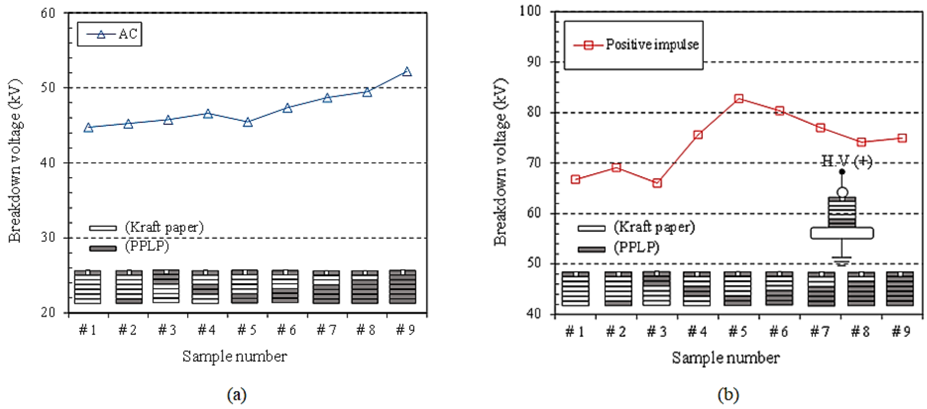


Figure 5. Breakdown voltage of PPLP/Kraft paper samples: (a) AC and (b) Impulse.

3.2. V-t Characteristics

Figure 6 shows *V-t* characteristics of Kraft paper, PPLP and PPLP/Kraft. It is observed that the correlation between applied voltage, *V*, and time to breakdown, *t*, follows the so-called inverse power law model expressed by equation (1), and *V-t* characteristics of investigated samples are depicted by the following equations (2), (3), (4), (5) and (6). Although the coefficient *A* is higher for PPLP due to higher breakdown voltage (see Figure 3), the lifetime index *n* becomes lower in the order of Kraft, PPLP/Kraft and PPLP. This indicates that a small increase in applied voltage causes a dramatic decrease in the lifetime of Kraft, so Kraft paper is more sensitive to over-voltage than PPLP/Kraft and PPLP samples. By contrast, with low value of *n*, PPLP shows a good resistance to over-voltage, but extrapolation to long lifetimes may yield an unacceptably low working stress. Due to these undesirable characteristics of both Kraft paper and PPLP, the composite insulation (PPLP/Kraft) becomes the best choice for both short-term and long-term working stresses in comparison with PPLP and Kraft paper. Compared to 1-layer samples, the value *n* of 3-layer samples is significant lower. This indicates that the “layer effect” or “thickness effect” considerately reduces the *n* by increasing the number of voids, air bubbles, impurities…that promotes breakdown processes. This result was previously reported by other researchers [5, 15].

$$V = A.t^{-1/n} \tag{1}$$

Where V is the applied voltage, n is the lifetime index and t is the time to breakdown.

$$V = 11.5t^{-1/35.7} \text{ (1-layer Kraft)} \tag{2}$$

$$V = 14.6t^{-1/31.3} \text{ (1-layer PPLP)} \tag{3}$$

$$V = 21.6t^{-1/33.3} \text{ (3-layer Kraft)} \tag{4}$$

$$V = 34.3t^{-1/16.7} \text{ (3-layer PPLP)} \tag{5}$$

$$V = 25t^{-1/27} \text{ (3-layer PPLP/Kraft)} \tag{6}$$

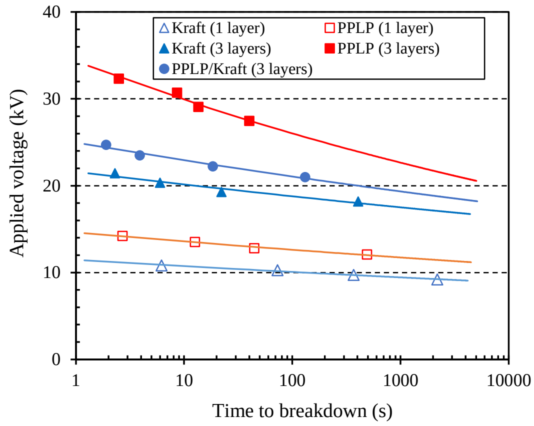


Figure 6. Correlation between applied voltage and time to breakdown.

3.3. Suggested mechanism for the breakdown in PPLP/Kraft composite insulation

On the basis of the experimental results shown in this study and those presented by other researchers [5, 16, 17], the mechanism behind breakdown in PPLP/Kraft composite insulation is proposed as follows. The breakdown begins in the butt-gap of the 1st layer because of partial discharges (PD) as shown in Figure 7a [16]. The reason is that the permittivity of LN_2 (ε_r = 1.4) is only about 65 % of that of PPLP (ε_r = 2.29) [18]. Thus, the electric field intensity considerately rises in the butt-gap, which promotes PD initiation in the butt-gap. In addition, the breakdown strength of PPLP in LN_2 is higher than that of LN_2, and PD is considered to be high enough to quickly damage and erode the 2nd layer by means of energetic electric charges, ultraviolet and temperature. At the same time, PD also occurs inside porous structure of PPLP [19]. Although, the trapping of positive charges formed by PD reduces the electric field close to the sphere, these charges will greatly increase the field further away from it (Figure 7b). This considerately enhances PD in the 2nd and 3rd layers. The combination between PD in butt-gap and PD inside the porous structure of PPLP further damages the PLPP layers and decreases its volume breakdown strength to a value that the discharges can puncture the PPLP layers. After puncturing, the discharges may either penetrate the next layer (channel 1) or creep on the layer surface (channel 2). This is dependent on the ratio of the volume breakdown strength to the surface breakdown strength of Kraft layer at this position. The volume breakdown strength of Kraft paper greatly depends on the number of voids, air bubbles and impurities, which promote PD inside the paper, while small liquid gaps at interface between layers, impurities and small protrusions on paper surfaces could significantly affect the surface breakdown strength.

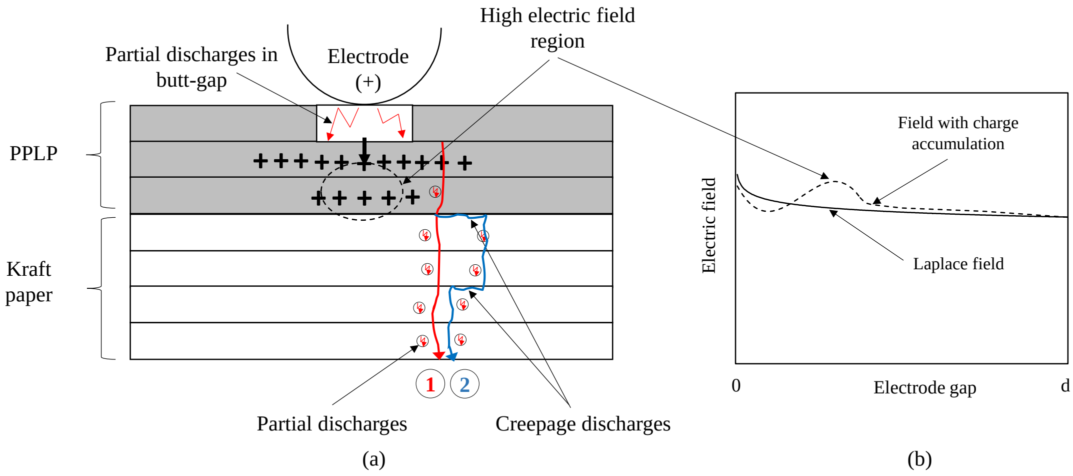


Figure 7. Breakdown mechanism: (a) charge accumulation and (b) electric field distortion.

4. Conclusion

Based on the experimental results, the following conclusions can be drawn. For AC applied voltage, PPLP has the highest breakdown strength among three investigated samples while PPLP/Kraft exhibits the best choice for impulse voltage application. Additionally, the lifetime index *n* of PPLP/Kraft is between that of PPLP and Kraft. Moreover, the accumulation of positive charges on PP film is suggested to cause a variation in breakdown voltage of PPLP/Kraft samples. Finally, the puncture of multi-layer insulation would be strongly dependent on the PD in the butt-gaps and inside insulation as well as electric discharges on the surface of insulation layer. Thus, with plain sample, PPLP/Kraft composite insulation shows the optimal insulation for HTS cable. However, it is aware that more experiments should be performed with tube models and mini cables in the next future.

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