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THE INFLUENCE OF POLYPROPYLENE LAMINATED PAPER ON THE BREAKDOWN STRENGTH OF INSULATION FOR HIGH TEMPERATURE SUPERCONDUCTING CABLE

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Abstract. Polypropylene Laminated Paper (PPLP) and Kraft paper has been used as power insulation for conventional cable as well as high temperature superconducting (HTS) cable operated with alternating current (AC) because of its prominent insulating characteristics. However, research on the use of PPLP/Kraft insulation for HTS cables are thinly scattered. In this paper, the effect of PPLP on the breakdown strength of PPLP/Kraft multi-layer sample impregnated with liquid nitrogen (LN_2) under AC and impulse applied voltage was studied. In addition, the breakdown strength characteristics of PPLP and Kraft samples were also investigated directly in order to determine breakdown strength characteristics of PPLP/Kraft insulation. It was found from the experimental data that the breakdown strength increases as the component ratio of PPLP in the PPLP/Kraft sample increases and is slightly affected by the inserting position of PPLP but in impulse case, the breakdown strength strongly depends on the number of PPLP and the relative position of PPLP.

Keywords: breakdown strength, HTS cable, liquid nitrogen, polypropylene, paper.

Classification numbers: 2.3.1, 2.8.3.

1. INTRODUCTION

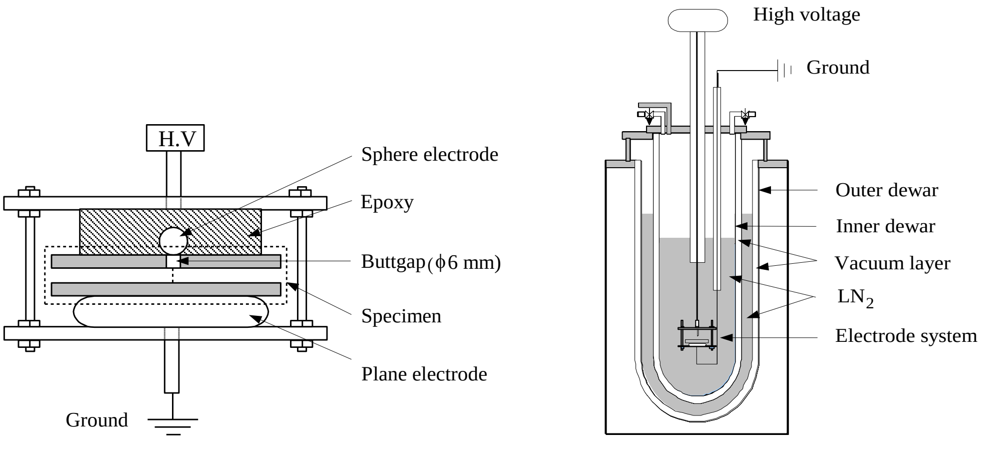
High temperature superconducting (HTS) cable is predicted to transmit high power densities with strongly reduced conductor loss at lower voltage because of the high critical current density of the HTS conductor compared to that of conventional copper ones [1, 2]. Polypropylene Laminated Paper (PPLP)/Kraft composite insulation has been used as oil-filled power cable insulation because of its lower dielectric loss and higher dielectric strength in comparison to ordinary Kraft [3]. Recently, PPLP and Kraft has been investigated for use as tape insulation for HTS power cables due to its ability to be easily impregnated with liquid nitrogen (LN_2) and its excellent dielectric characteristics, so its breakdown mechanism has been studied [4-9]. However, the lifetime index of the voltage-time characteristics of PPLP is lower than that of Kraft paper, and PPLP is more expensive than Kraft paper [4, 10]. Therefore, the combination between PPLP and Kraft paper were investigated in a previous study [10], and the result was obtained that PPLP/Kraft insulation has similar breakdown strength, partial discharges inception and dielectric loss factor to PPLP. However, the effect of position of PPLP layers on the breakdown strength of multi-layer insulation was not yet investigated. In addition, HTS cables may suffer AC voltage and both positive and negative impulses during over-voltages, but other researchers focused on AC voltage and positive impulse only [4, 8, 10, 11]. Positive impulse results in positive streamers while negative impulse generates negative streamers in insulating liquids in small gaps, *i.e.* butt-gaps, between consecutive turns of paper-insulated cables, and these types of streamers consist of electric charges which may affect the breakdown strength of PPLP/Kraft insulation [12, 13].

In this paper, the effect of PPLP on the breakdown strength of PPLP/Kraft was studied, as well as the breakdown strength of PPLP and Kraft, which were also considered, under AC and impulse voltage in order to understand clearly the breakdown strength characteristics of PPLP/Kraft insulation impregnated with LN_2.

2. MATERIALS AND METHODS

2.1. Experimental setup

Figure 1a shows the electrode configuration for the experiments. Multi-layer samples were laminated between sphere and plane electrodes. The diameter of the 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. Figure 1b shows a diagram of the experimental apparatus (the cryostat). The electrode system was set in a Dewar flask of LN_2 in the innermost layer of the cryostat with a high voltage bushing. The outer layer was filled with atmospheric liquid nitrogen (1 atm, 77 K) to prevent the temperature rise of the liquid nitrogen in the innermost layer. 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, which is made by Dae Yang Electric CO., LTD (1.2 × 50 μs, 400 kV, 15 kJ).



a. Electrode system *b.* Cryostat and experimental setup

Figure 1. Electrode system (a) and experimental setup (b).

2.2. Paper samples

The insulations used in this experiment are 0.1 mm thick Kraft paper and 0.119 mm thick PPLP, which consists of two sheets of Kraft paper of 0.025 mm laminated by extruded PP of 0.069 mm. Both Kraft paper and PPLP are made in Finland. Density of Kraft paper and PPLP are 0.72 g/cm^3 and 0.89 g/cm^3, respectively. Because of the highly hygroscopic nature of Kraft paper, vacuum drying of samples was performed at a temperature of 100 ^{o}C for 24 h prior to testing [14]. The moisture content of Kraft paper was 8.1 ± 0.15 % and 0.7 ± 0.19 % before and after drying, respectively. Similarly, the moisture content of PPLP significantly reduced from 5.8 ± 0.13 to 0.5 ± 0.09 %. For determining the breakdown strength characteristics of PPLP and Kraft multi-layer, two kinds of samples were used. These are samples with butt gap and without butt gap, and the number of layers was varied from two to seven. PPLP and Kraft paper were cut in square shape of 80 mm × 80 mm. A hole with diameter of 6 mm was punched in the first layer of specimens for simulating the existence of small butt gaps between consecutive turns of paper-insulated cables [10], and the butt gaps are the weakest points, at which partial discharges occur, in the multi-layer insulation [15]. In the case of studying the effect of PPLP on the breakdown strength of PPLP/Kraft multi-layer, we also used with butt gap sample, as shown in Fig. 2 and without butt gap sample, as shown in Fig. 3, in which the samples were divided into two cases: upper case (PPLP layers are at the top) and lower case (PPLP layers are at the bottom).

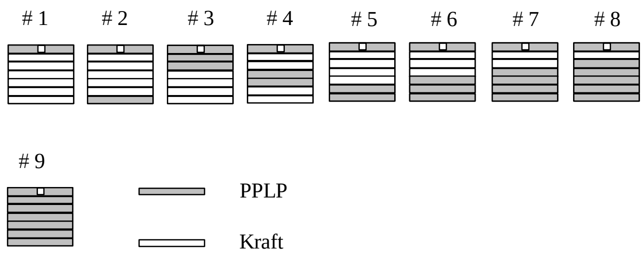


Figure 2. PPLP and Kraft layer configuration for the with butt gap samples.

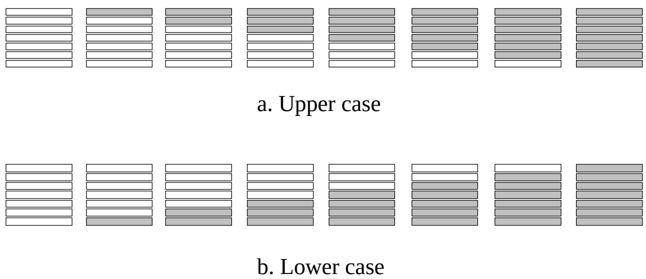


Figure 3. Upper and lower case configurations for the without butt gap samples.

2.3. Method and procedure

The AC breakdown test was carried out according to a standard method [16]. The test samples were subjected to a slow AC ramp (1 kV/s) one by one until breakdown occurred [16]. For the impulse test, firstly, a voltage estimated to be 70 % of the breakdown value was applied to the test object. The voltage was then increased in steps of 4 kV until a breakdown occurred [12]. The polarity of the applied impulse voltage was also changed. For both the AC and impulse tests, the breakdown test was repeated 10 times for each kind of samples to obtain an average value of the breakdown voltage. After each breakdown, a puncture sample was replaced with a new one.

3. RESULTS AND DISCUSSION

3.1. The breakdown strength characteristic of PPLP

The breakdown strength of PPLP multi-layers is presented in Fig. 4. It shows that the breakdown strength decreases linearly with increasing thickness. A reduction in the breakdown strength of PPLP insulation with increasing the number of layers or thickness was observed in references [4, 8]. However, the breakdown strength of without butt gap sample is higher than the samples with butt gap due to the effect of the butt gap, at which partial discharges occur and hence a lower breakdown voltage was obtained [6, 15]. Similar results were reported in references [4, 6, 15]. Moreover, in both cases, the impulse breakdown strength is much higher than the AC breakdown strength, and its standard deviation is also larger than that of the AC breakdown strength. The higher value of the impulse breakdown strength compared to the AC breakdown strength was previously observed in PPLP [8, 10, 11]. However, the value for a negative impulse is higher than that for a positive impulse due to the formation of positive streamers and the positive charges trapped on the surface of the PP film [12]. The polarity dependence of the breakdown strength of PPLP insulation was reported by other researchers [17]. However, the difference between negative and positive breakdown strength in this study is much larger than that observed in [17]. This is because the sphere-plane electrode system was used in this study while the more homogeneous electrode system, *i.e*. the coaxial system, was used in [17]. From this result, it is inferred that the polarity of the applied voltage has a strong effect on the breakdown strength voltage of PPLP. In addition, the decline of the impulse breakdown strength is larger than that of the AC breakdown strength, and the slope of the breakdown strength line for the without butt gap samples is much larger than that of the with butt gap sample. From these results, it is clearly seen that the impulse breakdown strength is more thickness dependent than the AC breakdown voltage, and the without butt gap samples also have a stronger thickness dependence than that of the with butt gap samples.

3.2. The breakdown strength characteristic of Kraft

Figure 5 shows the breakdown strength of Kraft as a function of thickness. The breakdown strength decreases linearly as the thickness increases, and the value of the breakdown strength in the without butt gap samples is always higher than that of the with butt gap samples. This result is in line with that observed by other researchers [4]. Moreover, the impulse breakdown strength is higher than the AC breakdown strength, and the standard deviation in the impulse case is also larger than in the AC case. The superior value of the impulse breakdown strength in comparison with AC breakdown strength of Kraft paper was reported in previous studies [10, 11]. However, there is a small difference in the breakdown strength between positive and negative impulses for both with and without butt gap samples as increasing the thickness. A similar result was observed with the testing of one sheet of Kraft paper [18]. This is possibly because positive and negative charges spread easily into Kraft paper [12]. It is clear that the polarity of the applied voltage has a little effect on the breakdown strength of Kraft paper. The slope of the impulse breakdown strength line seems to be parallel to that of the AC breakdown strength line in both with butt gap and without butt gap samples. However, the breakdown strength line in the without butt gap samples is much steeper than for the with butt gap sample. From these results, it is concluded that the effect of thickness on the breakdown strength of Kraft is only slightly dependent on the kind of applied voltage but strongly dependent on the state of the sample, *i.e.*, whether or not it has a butt gap.

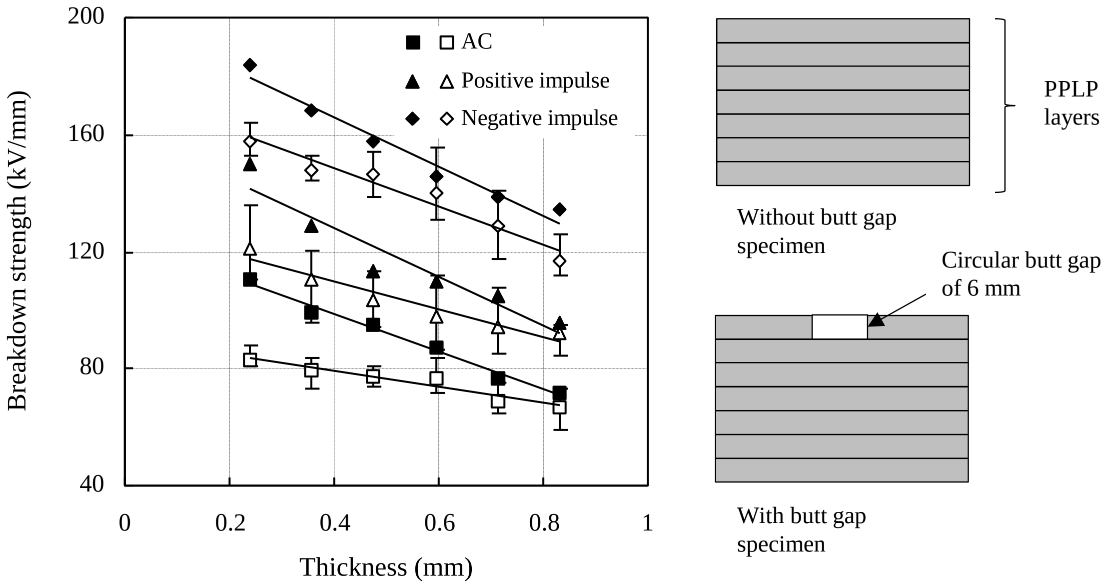


Figure 4. Breakdown strength versus thickness of PPLP. Full symbols for without butt gap; open symbols for with butt gap.

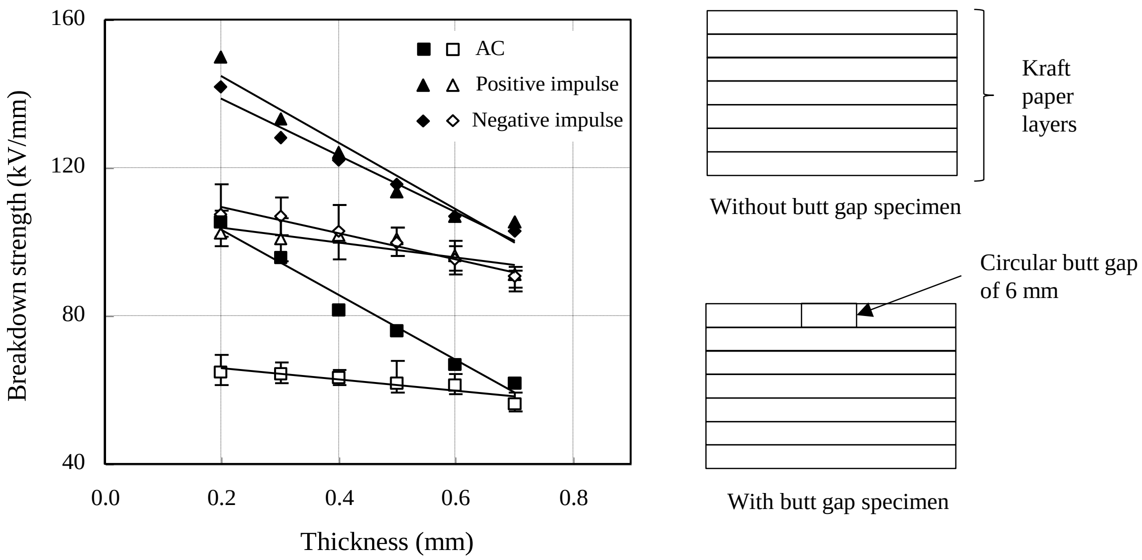


Figure 5. Breakdown strength versus thickness of Kraft. Full symbols for without butt gap; open symbols for with butt gap samples.

3.3. The breakdown strength characteristic of PPLP/Kraft

The comparison of breakdown strength between PPLP and Kraft paper with butt gap sample as a function of thickness is shown in Fig. 6. The breakdown strength and its standard deviation of PPLP are higher than those of Kraft. The similar result was previously reported in references [4, 5, 10]. This could be due to the partial discharges occurring inside porous structure of Kraft paper, but this is not the case of PP layer [18]. However, the difference in the value of the breakdown strength between PPLP and Kraft becomes smaller as the thickness increases for positive impulse case. In addition, the slope of the breakdown strength line of PPLP tends to be steeper than that of Kraft, so the thickness of PPLP has a more significant effect on the breakdown strength characteristics as compared to Kraft paper.

The breakdown strength of PPLP/Kraft for the without butt gap sample is shown in Fig. 7. It shows that the value for the impulse case is higher than that of the AC case and the value for the negative impulse case is highest. The breakdown strength strongly increases as the number of PPLP layers increases in the PPLP/Kraft samples for the negative impulse case, and just slightly increases for the positive impulse and AC cases. This result is in agreement with that observed under AC and positive impulse [10]. Moreover, the AC breakdown strength varies only slightly for both the upper and lower cases, but the impulse breakdown strength shows somewhat more clear difference between the upper and lower cases. However, the difference in the values between the upper and lower cases is larger for the negative case. From these results, it shows that the number of PPLP in PPLP/Kraft has a strong effect on the negative impulse breakdown strength and a slight effect on the AC and positive impulse breakdown strength. However, the inserting place of PPLP in PPLP/Kraft has a strong effect only on impulse breakdown strength for the negative impulse.

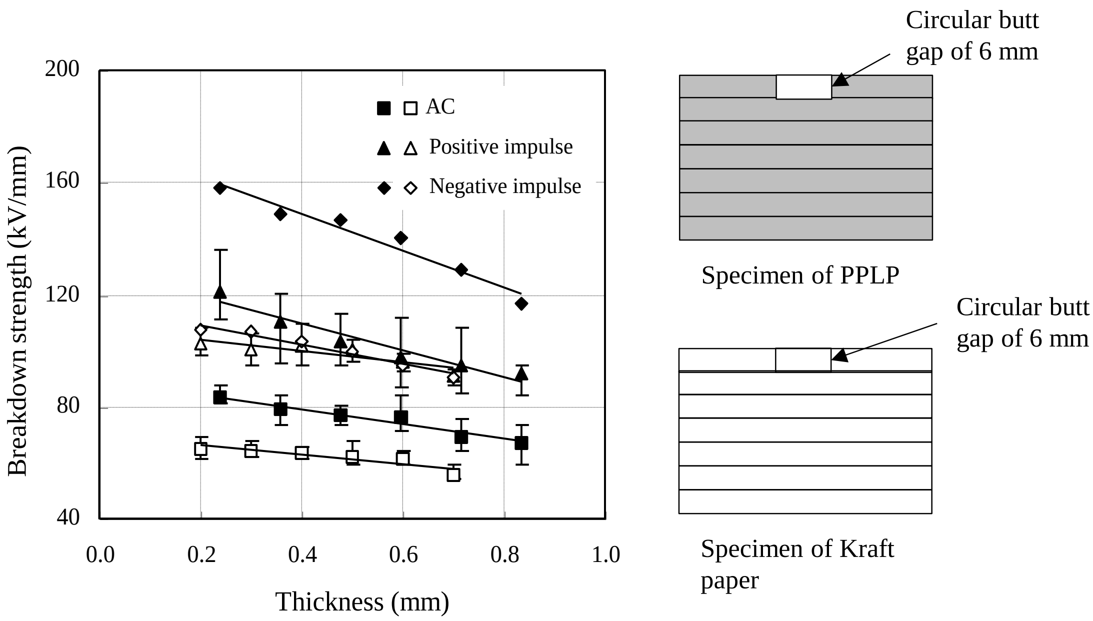


Figure 6. Breakdown strength comparison. Full symbols for PPLP; open symbols for Kraft samples.

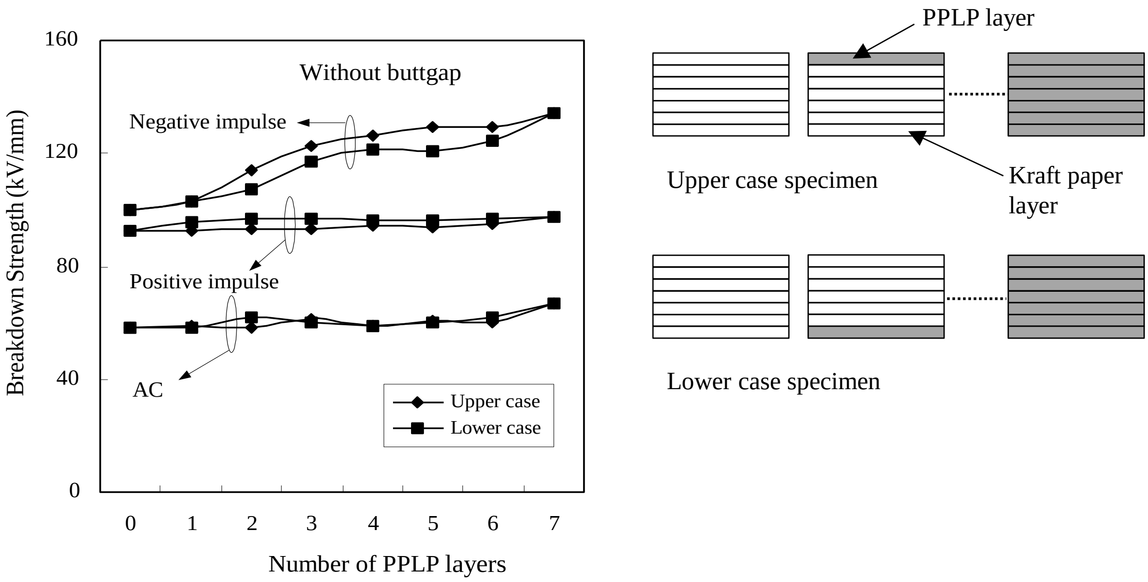


Figure 7. Breakdown strength of PPLP/Kraft for the without butt gap samples.

The breakdown strength of PPLP/Kraft with butt gap samples is shown in Fig. 8. It shows that the AC breakdown strength increases as the number of PPLP layers in PPLP/Kraft increases, and the value of specimen #9 (PPLP only) has the highest value while specimen #1 (Kraft only) has the lowest value. However, the breakdown strength varies only slightly as the inserting place of PPLP (see #3, #4, #5) changes. These results was observed by other researchers [19]. The results show that the AC breakdown strength of the PPLP/Kraft specimens is only slightly affected by the relative position of PPLP in the specimen but rather strongly affected by the component of PPLP and Kraft paper in PPLP/Kraft sample. The reason could be considered that PPLP has a higher partial discharges proof compared to Kraft paper [19]. The partial discharges may occur both in the butt-gap and interfaces between layers. The positive impulse breakdown strength of PPLP (#9) is a little higher than that of Kraft paper (#1) due to the effect of the layer thickness of the latter. The breakdown strength varies greatly as the component ratio of PPLP and Kraft in PPLP/Kraft varies, and the value of specimen #5 has the highest value in comparison with those of specimens #3 and #4, which indicates that the breakdown strength becomes larger as the distance of the PPLP from positive electrode, i.e. the spherical electrode, becomes larger. This is due to the effect of trapping positive charges, which are formed by positive streamers in the butt gap, by PP film, leading to increase the local electric field intensity as seen in Fig. 9 [12]. When the distance from the PPLP to the positive electrode increases, therefore, positive charges have a change to spread into Kraft paper and hence the accumulation of positive charges on the surface of PP film reduces. This results in a lower local electric field and higher breakdown strength. The breakdown strength varied depending on the number and the position of PPLP in PPLP/Kraft as observed in specimen #5 which is in line with that observed in references [10, 12]. This explains why the impulse breakdown strength of PPLP/Kraft is higher than that of Kraft or PPLP alone.

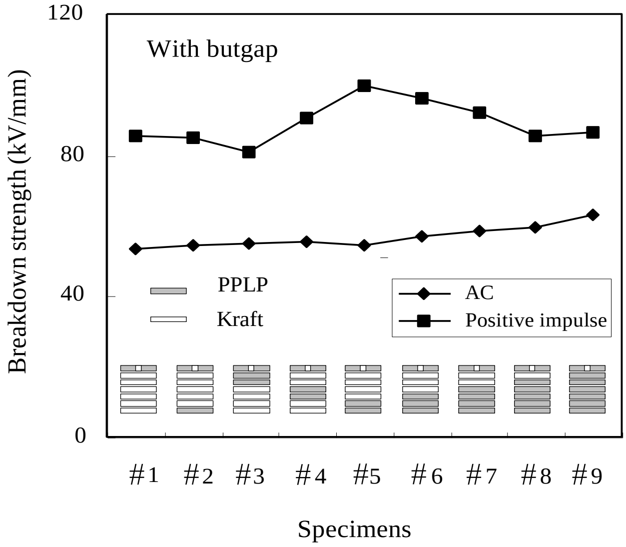


Figure 8. Breakdown strength of PPLP/Kraft for the with butt gap samples.

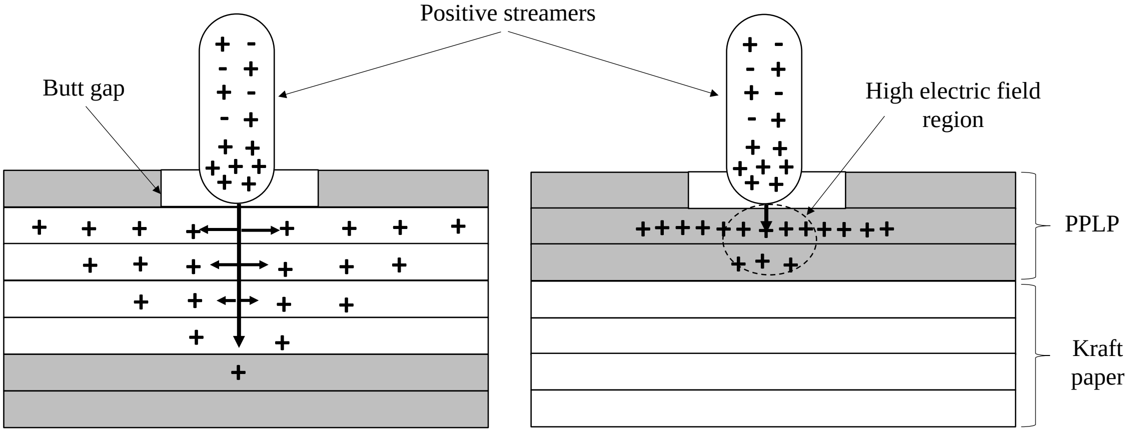
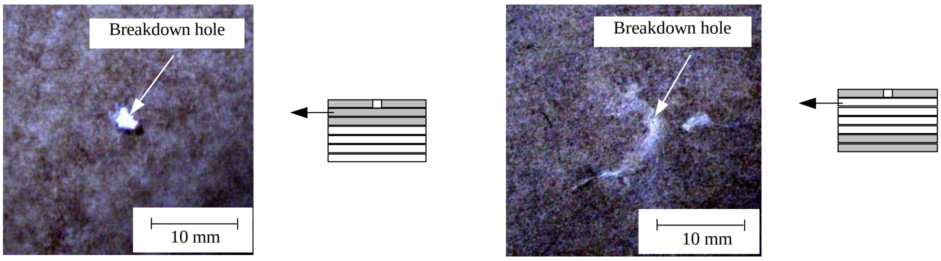


Figure 9. Charge accumulation on PPLP



a. Positive impulse breakdown spot on PPLP layer

b. Positive impulse breakdown spot on Kraft layer

Figure 10. Images of positive impulse breakdown spots.

Figure 10 shows the breakdown-spot images of the PPLP layer in specimen #3 and Kraft layer in specimen #5 after positive impulse breakdown. The breakdown spot of the PPLP layer is obvious, and the breakdown hole is big. On the other hand, the breakdown spot of the Kraft layer looks complicated, and breakdown hole is small. This result is due to the fact that positive charges are trapped on the surface of the PPLP, while they can spread easily into Kraft paper. Similar images were captured for PPLP and Kraft paper in a previous study [12].

4. CONCLUSIONS

The breakdown characteristics of PPLP/Kraft insulation was performed, and the experimental results show that PPLP has a significant effect on the breakdown strength of PPLP/Kraft insulation. In the AC case, the breakdown strength is greatly dependent on the component of PPLP in the PPLP/Kraft sample but only slightly dependent on the relative position of the PPLP due to high partial discharges proof of PP film. In the impulse case, the breakdown strength of PPLP/Kraft has the highest value in comparison with PPLP or Kraft. The impulse breakdown strength of PPLP/Kraft is strongly dependent on the component of PPLP and the position of the PPLP. This is due to the accumulation of positive charges on PPLP layer which increases the local electric field intensity. On the breakdown strength aspect, PPLP/Kraft composite insulation exhibits the best insulation in comparison with PPLP and Kraft.

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