Evaluation of Insulating Materials for HVDC Transmission Cable using Space Charge Measurement

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SUMMARY

Some large HVDC (High Voltage Direct Current) electric power transmission networks are under contemplation in Europe area. To establish the HVDC network, a long distance DC cable must be developed. From an economic point of view, maintenance-free XLPE (cross-linked polyethylene) cable is preferable rather than traditional OF (oil-filled) cable for the future HVDC network. However, it is usually said that the space charge accumulates in the insulating layer of the XLPE cable under dc high stress, and it is believed that a distorted electric field induced by the space charge accumulation leads an electrical breakdown. Therefore, it is necessary to investigate the space charge characteristics in the developed material for the HVDC cable under dc high stress.

We have investigated the relationship between the space charge accumulation and the breakdown in a LDPE (low-density polyethylene), a base material of XLPE, under dc high stress using so-called PEA (pulsed electro-acoustic) method. We have found through the study that a huge amount of, so-called, a “packet-like charge” has been injected into the bulk of LDPE, and the distorted electric field by the packet-like charge accumulation has led the breakdown as it has been prospected. However in XLPE, the breakdown occurs with different process from that in LDPE. Many researchers have pointed out that the existence of residues of cross-linking by-products in XLPE may be the reason why the space charge accumulation characteristics in XLPE are different from those in LDPE.

To understand the breakdown process in XLPE, we have investigated the time dependent space charge density, electric field and conduction current density distributions under dc high stress. Furthermore, we also estimate the dissipation power density distribution. Judging from the results on XLPE under dc high stress, it was suggested that the heat generation was dominant factor for the breakdown in XLPE under high dc stress.

As noted above, the measurements of the space charge distribution and the external current in materials under dc high stress are important to show their performance as the insulating layer of power transmission cable for HVDC network. In this report, I would like to introduce some typical results of the space charge accumulation in various insulating materials and show the importance of such measurements on the estimation of insulating materials for HVDC cable.

KEYWORDS

Space charge, DC breakdown, LDPE, XLPE, Insulating material for DC cable

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1. Introduction
In the recent decade, HVDC (High Voltage Direct Current) must be one of most important keyword for researchers working in a field of electrical insulating materials. While the HVDC networking concept has been launched from Europe area, it must reach global proportions accompanying revolutionary changes of the insulating materials in near future. To realize the network, the materials are subjected to dc high electric field and it is necessary to develop the materials which show a good performance under high dc stress. With such a research back ground, we have investigated the performance of polyethylene [1], which is used for the insulating layer of the power transmission cable. Judging from our previous work [1], a space charge accumulation in low-density (LDPE) strongly affects its breakdown characteristics. Therefore, it was supposed that the space charge accumulation also must affect the breakdown properties in cross-linked polyethylene (XLPE), which is used for the actual transmission cable. However, while the space charge accumulation in LDPE showed the clear relationship with the breakdown, it was not obvious in XLPE [2]. In LDPE, a large amount of so-called “packet-like charge” was injected in the bulk and it enhanced a local electric field [1]. When the enhanced electric field reached a certain value of intrinsic breakdown strength, the breakdown seemed to occur in LDPE [1]. On the other hand, the breakdown occurred in XLPE without any clear sign in the space charge measurement results [2]. Therefore, we need to add some adequate experimental facts to understand the breakdown in XLPE under high dc stress. A chemically cross-linked XLPE is originally including some impurities of cross-linking byproducts, while LDPE is not including such impurities. It is well known that such impurities can cause a higher conduction current in XLPE than that in LDPE under dc high stress. It can be thought that the large current in XLPE is one of significant factor for the difference between them. Therefore, we tried to measure the conduction current in a sample simultaneously with the space charge measurement using an improved pulsed electro-acoustic (PEA) [3] measurement system [4].

2. Samples and Experimental Procedure

2.1 Samples
Nominally additive free low-density polyethylene (LDPE) and cross-linked polyethylene (XLPE) were used. LDPE was formed into a film shape with thickness of 100 - 150 µm or less than 100 µm using hot-pressing or inflation process. XLPE was made of LDPE by chemical cross-linking process using decumyl peroxide (DCP), and it was also formed into a film with thickness of 100 - 150 µm using hot-press process. For a cable insulating layer with thickness of more than 10 mm, XLPE is usually including some volatile chemical by-products like acetophenone, cumyl alcohol and α-methyl styrene. On the other hand, they are usually volatilized soon from the thin film like 100 µm-thick even at room temperature. Therefore, to keep the sample under the similar condition of the cable insulating layer, XLPE film was kept in aluminum foil just before the measurement to keep the cross-linking by-products in the sample. Furthermore, a degassed XLPE, which was assumed not to be including the cross-linking by-products, was also prepared. To make the degassed one, XLPE was kept in vacuum chamber for one hour. The degassed sample is described as “XLPE/dry” in this paper.

2.2 Space charge measurement
Time dependent space charge distributions in the samples till breakdown under very high dc electric field were observed using PEA method [3]. In ordinary PEA system, a semi-conductive layer and an aluminum plate are used as a high voltage (upper) supplying and grounded electrodes. The semi-conductive layer is used to improve acoustic impedance between sample and electrode. All measurement results in this paper were obtained using the layer as anode electrode. We needed to measure an external current, which is usually called as “conduction current”, simultaneously with the space charge measurement as will become appear below. Therefore, we used an improved system to measure them simultaneously [4]. Using the system, we can measure them by switching the connection of the current and the space charge distribution measurement circuits alternatively. The timing of the switching is controlled using a computer. From the obtained data, we can calculate time dependent electric field, conduction current, displacement current, and dissipation power distributions. Details of the measurement are described elsewhere [4].
3. Results and discussion

3.1 Space charge accumulation process till breakdown

Figures 1 (a) and (b) show typical time dependent (1) space charge behaviors described using color chart, (2) profiles of charge density distributions and (3) electric field distributions till breakdown in LDPE and in XLPE, respectively. They were obtained under an average electric field (= applied voltage / sample thickness) of 330 and 200 kV/mm in LDPE and in XLPE, respectively. A blue and a red lines in Figs. 1 (b) and (c) show the first (0 min.) and last (just before breakdown) distributions, respectively. A large amount of positive packet-like charge injection was observed in LDPE as shown in Fig. 1 (a-1). The injected positive packet-like charge moved towards cathode side, and then a breakdown occurred in the sample. The amount of the packet-like charge was gradually increased with time as shown in Fig. (2-b). When the breakdown occurred in the sample, the maximum electric field was about 550 kV/mm, which was located between the packet-like charge and the cathode as shown in Fig. 1 (a-3), and then a breakdown occurred after it stopped around the middle of the sample.

On the other hand, the process to breakdown in XLPE seems to be completely different from that in XLPE as shown in Figs. 1 (b-1) and (b-2). Adding to the positive packet-like charge injection, a negative charge was also observed. In this case, both of the positive and the negative packet-like charges were injected into the sample and they passed through the sample. Then, the positive packet-like charge disappeared near the cathode, and it injected again. On the other hand, a part of negative charge seemed to remain near the anode. While the positive charge behavior sequence of injection; movement across the sample and disappearance near the cathode was repeatedly observed, the amount of injected charge decreased gradually, and finally the injection discontinued within 10 minutes. After the space charge distribution became stable, a breakdown occurred in the sample suddenly at about 28 minutes later. As shown in Fig. 1 (b-3), while the position of maximum electric field moved depending on the change of the space charge distribution, it becomes stable with relatively low value as described using red line in Fig. 1 (b-3).

To analyze the effect of the electric field in the sample on the breakdown, we had investigated the time dependent maximum electric field in LDPE under various applied electric fields [1]. Figure 2 shows the time dependent maximum electric field in LDPE at each distribution under various applied dc
electric fields. Judging from the results, it is found that the breakdown occurred in this LDPE sample when the maximum electric field reached in a range between 550 and 600 kV/mm. It can be thought that the intrinsic breakdown strength of this LDPE sample is between 550 and 600 kV/mm. Therefore, the breakdown must occur when the electric field in the sample reached to the breakdown strength. However, in the ordinary test without the space charge observation, the breakdown strength is recognized as the applied electric field. That may be one of reasons why the breakdown characteristics of LDPE under dc voltage show some complicated aspects.

On the other hand, Figure 3 shows the time dependent maximum electric field in XLPE calculated from the results shown in Fig. 1 (b). In this case, the maximum electric field once increased to relatively high value of about 350 kV/mm within a few minutes after beginning of voltage application. However, the breakdown did not occur at that time, and then the maximum electric field gradually decreased and it became stable around 250 kV/mm. It seems to be that the breakdown suddenly occurs under the stable electric field condition. It means that the process to breakdown in XLPE is completely different from that in LDPE.

3.2 Breakdown process in degassed XLPE
Many researchers have pointed out that the existence of cross-linking by-products strongly affect to the space charge formation. However, there are few reports that show the relationship between the existence of them and breakdown process obviously. Therefore, we tried to show the effect by observing the space charge behavior in degassed XLPE under dc high stress till breakdown. Figure 4 shows the time dependent space charge behaviors in degassed XLPE (XLPE/dry) under the applied electric fields of (a) 100, (b) 200 (c) 300 and (d) 330 kV/mm. As shown in Fig. 4 (a), while the positive packet-like charge was observed under the applied electric field of 100 kV/mm, the amount of it was not so large and it gradually disappear before it reached on the cathode. In the case under 200 kV/mm as shown in Fig. 4 (b), after the relatively large amount of packet-like charge injection, a negative charge accumulation was also observed near the anode. In this result, the positive packet-like charge moved across the sample, while the packet-like charge stopped in the middle of bulk in LDPE. After crossing the sample, the packet-like charge disappeared and the second injection seemed to start. Since a similar phenomenon was observed in XLPE, we assume that the negative charge accumulation might induce the difference of charge accumulation behavior in XLPE from that in LDPE. In other words, when the negative charge accumulates in the bulk, the repetition of positive packet-like charge injection might be induced in the sample. Under the applied electric field of 300 kV/mm, a large amount of packet-like charge was injected from anode and it moved towards cathode as shown in Fig. 4 (c). In this case, the accumulation of the negative charge is not obvious, and its pattern is close to that in LDPE shown in Fig. 1 (a-1). The breakdown was observed under the applied electric field of 330 kV/mm as shown in Fig. 4 (d). In this case, the breakdown occurred in the process of the positive

![Figure 4](image-url)

Figure 4. Time dependent space charge accumulation behavior in XLPE/dry under various applied electric fields.

![Figure 5](image-url)

Figure 5. Time dependent maximum electric field in XLPE/dry under various applied electric field.
packet-like charge travelling towards cathode without the accumulation of the negative charge. Therefore, the breakdown mechanism must be similar to that in LDPE shown in Fig. 1 (a-1).

Figure 5 shows the time dependent maximum electric field in XLPE/dry at each distribution shown in Fig. 4. Under 100 and 200 kV/mm, the maximum electric fields once increased with time, and then it decreased and again increased. The changes of the maximum electric fields seems to reflect the repetition of charge injection and it can be thought that the properties are little similar to the characteristics in XLPE shown in Fig. 3. On the other hand, the maximum electric fields increased monotonically under the applied electric field of 300 and 330 kV/mm, and these properties are very close to that in LDPE as shown in Fig. 2. Especially under 330 kV/mm, the breakdown occurred at about 400 kV/mm after monotonically increase. Since the breakdown occurred at the peak value of the maximum electric field, we can say that the breakdown process of it is a type of LDPE. The main difference between the XLPE and XLPE/dry must be the amount of cross-linking by-products in the bulk of samples. Therefore, it is obvious that the existence of the cross-linking by-products makes to show the different breakdown process in XLPE from that in LDPE.

3.3 Relationship between breakdown and conduction current

Figures 6 (a) and (b) show the results obtained from the simultaneous measurements in LDPE and XLPE, respectively. In the figures, time dependent (1) external current densities and (2) space charge density, (3) electric field, (4) conduction current density and (5) dissipation power density distributions are shown observed under 150 kV/mm. In these distributions, the horizontal and the perpendicular axes stand for the voltage application time and position in direction of sample thickness, respectively.

Figure 6 (a-1) shows the time dependent external current density in LDPE. In LDPE, the current quickly decreased and became a stable at a relatively low value of a few μA/m². A large amount of positive packet-like charge was observed in LDPE as shown in Fig. 6 (a-2), and it was basically similar to the result in Fig. 1(a) except for the existence of a small amount of negative charge injection. The electric field between the cathode and the injected packet-like charge was relatively high, and that in the area passed by the packet-like charge was relatively low as shown in Fig. 6 (a-3). In Fig. 6 (a-4), the conduction current density distribution in LDPE was described using the maximum scale of 150 μA/m² to compare with that in XLPE. In this scale, the conduction current was too small to be recognized anywhere and anytime in the measurement. Therefore, the dissipation

Figure 6. Time dependences of (1) external current densities and distributions of (2) space charge densities, (3) electric fields, (4) conduction current densities and (5) dissipation power densities in (a) LDPE and (b) XLPE under dc applied electric field of 150 kV/mm.
power distribution show in Fig. 6 (a-5) was also small anywhere and anytime while the high electric field was locally observed as shown in Fig. 6 (a-3).

On the other hand, the external current density in XLPE repeatedly increased and decreased, and then its average became gradually decreased as shown in Fig. 6 (b-1). At 60 minutes later, the current density was about 80 $\mu$A/m$^2$ and it was several tens times larger than that in LDPE. As shown in Fig. 6 (b-2), the positive and the negative charge injections were repeatedly observed in XLPE, and that was similar to the result shown in Fig. 1 (b). The repetition period seems to be almost the same to the period of increase and decrease cycle in the external current density shown in Fig. 6 (b-1). Judging from the electric field distribution shown in Fig. 6 (b-3), it is found that the electric field distribution was drastically changing with the voltage application time. While the maximum electric field showed once very high value just after the beginning of the voltage application, it gradually decreased. The conduction current density and dissipation power distributions in XLPE shown in Fig. 6 (b-4) and (b-5) were completely different from those in LDPE. Compared with the distributions in LDPE, both of the conduction current density and dissipation power were much larger than those in LDPE as shown in Figs. 6 (b-4) and (b-5). The large dissipation power must induce a heat generation in the sample. Therefore, these results suggest the thermal breakdown process may occur in the XLPE sample under high dc electric field. However, since it is difficult to estimate such obtained dissipation power can induced the thermal breakdown at this moment, further investigation should be carried out in near future.

Anyway, the thermal breakdown may occur under high dc electric field in XLPE including cross-linking by-products. Since the thermal breakdown must strongly depend on the thermal and configuration conditions of the insulating material, it is difficult to expect the breakdown in XLPE. If the cross-linking by-products are removed from XLPE, the electronic breakdown process must be dominant as well as that in LDPE. However, there is a possibility to prevent the breakdown caused by the packet-like charge generation using nano-composite technology [1]. Therefore, it is important to analyze more details of the breakdown process in XLPE to develop a good material for HVDC system.

4. Conclusion
The relationship between a space charge accumulation process and a breakdown under high dc stress in LDPE and XLPE were investigated using a PEA measurement system. While the breakdown occurs under a high enhanced electric field by a large packet-like charge accumulation in LDPE, a large conduction current may play a dominate role for the breakdown in XLPE under high dc stress.

References