Charge accumulation characteristics of modified XLPE for direct current usage at polarity reversal

Hiroki **KASUGA**, Toshiyuki **FUJITOMI**, Hiroaki **MIYAKE**, Yasuhiro **TANAKA;** Tokyo City University, (Japan), g1681210@tcu.ac.jp, fujiyan0@gmail.com, hmiyake@tcu.ac.jp, ytanaka@tcu.ac.jp

Hiroki **MORI**, Saki **KIKUCHI**, Yukihiro **YAGI;** Furukawa Electric Co., Ltd., (Japan), hiroki.hm.mori@furukawaelectric.com, saki.sk.kikuchi@furukawaelectric.com, yukihiro.yy.yagi@furukawaelectric.com

ABSTRACT

Space charge accumulation processes in a chemically cross-linked polyethylene for ac (XLPE) and a modified XLPE for dc (DC-XLPE) usages at voltage polarity reversal have been investigated using pulsed electro-acoustic (PEA) measurement system. In the measurements, adding to the observations with an electrode system composed of SC (semi-conductive layer: high voltage electrode) and Al (grounded electrode), the observations was carried out using SC (high voltage) and SC(grounded) electrode system, which were much closer to the condition of actual insulating materials of power cables. We found that a huge amount of so called packet-like charge, some of which partially increased the electric field in the material to more than twice of the average applied stress, generated in XLPE at the polarity reversal of applied DC stress. On the other hand, we also found that the any obvious packet-like charge was not observed in DC-XLPE under the same experimental condition.

KEYWORDS

Space charge, XLPE, PEA method, Polarity reversal

INTRODUCTION

Space charge accumulation property in cable insulating materials at voltage polarity reversal is one of important research objects in HVDC (High Voltage Direct Current) system. In a LCC (line commutated converter) system, the polarity reversal is necessary to change a direction of current flow. Even in a VSC (voltage-sourced converter) system, when an accident like a grounding fault or a lightning strike, a huge surge voltage of the inverse polarity may be applied to the cable insulating material.

On the other hand, it is said that the space charge accumulation sometimes strongly affects the breakdown characteristics of the materials. Previously using a pulsed electro-acoustic (PEA) method [1], we had observed that a large packet-like charge distorted electric field distribution in LDPE (low density polyethylene) and it induced electrical breakdown under a high dc stress [2, 3]. However, there were few attempts for the measurement of the space charge accumulation at the polarity reversal of very high dc voltage [4], while many engineers have pointed out that the polarity reversal test on a conventional XLPE (cross-linked polyethylene) cable showed somehow dangerous results including the breakdown. The space charge accumulation has been thought as the reason of the accidents. Therefore, we tried to study the relationship between the space charge accumulation property and the electric field distortion at the polarity reversal.

At first, we prepared some fresh samples including cross-linking by-products, then we tried to investigate the space charge accumulation behavior at the polarity reversal of very high dc stress in the fresh XLPE thin film. Furthermore, we measured it in a newly developed insulating material for dc cable. The space charge distributions were observed using the PEA measurement system. Furthermore, we tried to study the effect of semi conductive (SC) electrode on the space charge accumulation properties in the above samples. In an ordinary PEA measurement system, a SC layer is usually inserted between a high voltage metal electrode and the sample to match the acoustic impedance between them [5], while the sample is directly put on a grounded aluminum (Al) electrode. In this investigation, we also tried to measure the space charge accumulation characteristics in the sample which was sandwiched by the SC layers. When the SC layer is inserted between the grounded Al electrode and the sample, the acoustic signal is attenuated by the layer and the measurement spatial resolution is reduced. However, since the actual insulating layer of the power cables is sandwiched by the SC layers, we tried to measure the space charge distribution in the sample with a similar condition to the actual cable configuration by ignoring the reduction of the spatial resolution.

SAMPLE AND EXPERIMENTAL PROCEDRE

Samples

Chemically cross-linked polyethylene (XLPE) films were made from commercially available low density polyethylene (LDPE) using cross-linking agent of dicumyl-peroxide (DCP) by hot-press procedure. Their thickness was about 150 μm. Any anti-oxidation agent was not used. Since some crosslinking by-products are easy volatile from such thin films in air atmosphere, the films were kept by packing them in aluminum foils to prevent by-products diffusion. The films were removed from the foils just before the experiments. As it was shown in a previous report [6], it was confirmed that the crosslinking by-products of acetophenone and cumyl alcohol were still remaining in the films for several hours after the removal of the foils [6]. In the measurement, the samples were used within a few minutes after the removal. It means that they should remain in thin films just after the removal of the aluminum foils. In this report, we describe the fresh samples used just after the removal of the foils as "XLPE/F".

Furthermore, we investigated the space charge behavior at the polarity reversal in a newly developed XLPE [6] based material for HVDC cable insulation. The material is cross-linked polyethylene modified with functional group/without nano materials. to apply the cable for HVDC system. By reason of getting a patent, we cannot reveal the details of the material. In this paper, we call it "DC-

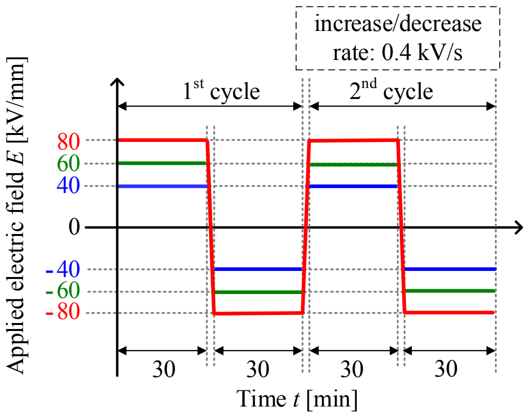


Fig. 1: Stress application sequence.

XLPE". As shown in previous report [6], the volume resistivity of DC-XLPE was higher than XLPE/F at all measured temperatures between 20 and 90 °C.

Experimental Procedure

Time dependent space charge behaviors in the samples under a certain dc stress were observed using the PEA method. At first, we studied the effect of the SC electrode. In this experiment, the space charge accumulation properties were observed in degassed XLPE (XLPE/D) under relatively high DC stress using SC-Al and SC-SC electrode systems. In these measurements, it was found that the effects of the SC grounded electrode were not obvious at room temperature (RT) under relatively low DC stress. Therefore, we tried to measure them under relatively high DC stress (150 kV/mm) at RT (ca. 30 °C) and 40 °C. When the temperature of the sample is increased, the cross-linked by-products are easy to volatilize from the thin XLPE sample. Therefore, in this study, we used the XLPE/D sample which was expected to be stable of small amount of the cross-linking by-products. The XLPE/D was prepared by kept in a vacuum chamber at 80 °C under a pressure of 10^{2-5} Pa order. The details of the degassed process were described elsewhere [7].

In the measurements including the voltage polarity reversal, the following two cycle observations were carried out for each sample. Figure 1 shows the time sequences of various stress applications to the samples. At first, a certain positive or negative voltage corresponding to average stress of 60 or 80 kV/mm was applied to the sample and the time dependent space charge distribution was measured for 30 min. Then the voltage polarity was reversed. After the polarity reversal, a time dependent space charge distribution was also observed for 30 min. In this report, we described the above measurement sequence as "1st cycle". At the polarity reversal, the voltage was varied with a steady rate of 0.4 kV/s. Therefore, the required time for the polarity reversal depended on both of the sample thickness and the applied stress. For example, when the sample thickness and the applied stress are 150 μm and positive 60 kV/mm, respectively, the positive voltage of 9 kV (= 0.15 mm x 60 kV/mm) was applied to the sample, and it took 45 s (= 9 x 2 kV / 0.4 kV/s) for the polarity reversal. In this report, the polarity of the stress is described as the polarity of the high voltage electrode.

RESULT AND DISCUSSION

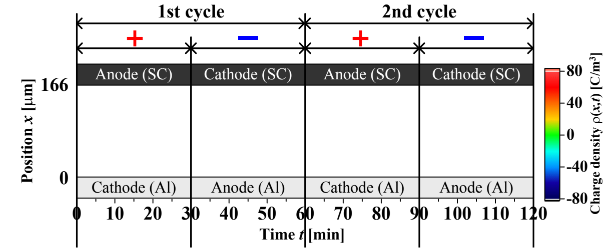
Space Charge Accumulation in XLPE

At first, we would like to show the measurement results of the space charge accumulation properties in XLPE/F at RT using the normal SC-Al electrode system. Figures 2a, 2b and 2c show the time dependence of space charge, electric field and maximum electric field in XLPE/F under positive dc stress of 60 kV/mm according to the stress sequence. Here, the electric field distribution was obtained using integral calculation from the space charge distribution.

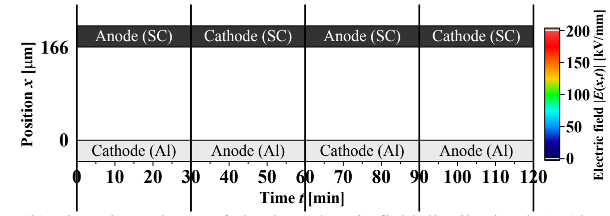
As shown in Figure 2a, a small amount of positive charge generation and movement were observed in the first 30 min. In this term, the maximum electric field was relatively stable with value of 70 kV/mm that was only about 17 % larger than the applied stress of 60 kV/mm. On the other hand, the large amount of positive "packet-like charge [8]" injection (ca. 40 C/m^3) was obviously observed at the voltage polarity reversal, and it moved across the bulk of the sample. The electric field was enhanced significantly and it reached a peak value of ca. 110 kV/mm that was more than 80 % larger than the applied stress of 60 kV/mm, as shown in Fig. 2c. In the second cycle, the similar behaviour to the first cycle was also observed in the experiment.

Figure 3 shows the measurement result obtained under stresses of ±80 kV/mm. In this case, while it is not clear using this colour scale in Figure 3a, small amounts of positive and negative charge injections (less than 15 C/m^3) near anode and cathode electrodes were repeatedly observed for the first 30 min. (Of course, the details were clearly shown if a lower colour scale was selected. However, to show the following data clearly, a larger scale was selected here.) The enhanced electric field was about 100 kV/mm (increased by 20%), while more than it was observed at the beginning of the voltage application, as shown in Figure 3c. On the other hand after the first polarity reversal, a huge amount of packet-like charge injection (ca. 70 C/m^3) from the anode was repeatedly observed. Such repetition of the packet-like charge injection was usually observed in XLPE/F under relatively high dc stress [9]. In this case, the enhanced electric field was also huge and it reached a peak value of ca. 190 kV/mm as shown in Figure 6c, and it was a whopping more than 130 % larger than the applied stress of 80 kV/mm. Under this condition, the space charge and electric field distribution in the 2nd cycle was a little different from those observed in the 1st cycle. After the second polarity reversal at 60 min, the packet-like charge injection was observed repeatedly even under positive stressing term. However, the enhancement of the electric field was not so large in this term compared with that observed in the negative stressing term. After the third polarity reversal at 90 min, the huge packet-like charge injection was observed again. However, the peak value of the maximum electric field was a little smaller than that observed in the first negative stressing term.

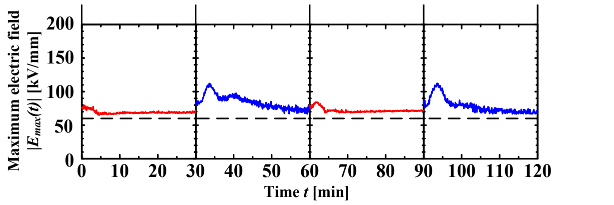
As mentioned above, it is found that a relatively large amount of packet-like charge is injected from anode electrode into the bulk of XLPE/F at the polarity reversal from positive to negative stresses, and it enhances the local electric field significantly. In the case of LDPE, such packet-like charge was not observed under dc stress of, at least, less than 100 kV/mm [3]. Therefore, the main



(a) Time dependence of space charge distribution $\rho(x,t)$

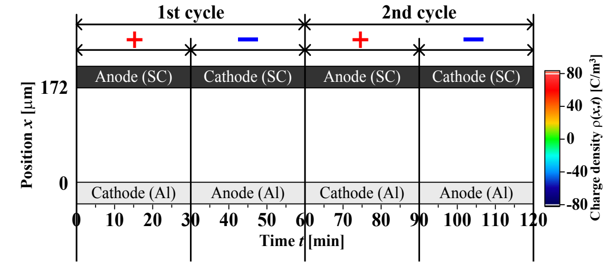


(b) Time dependence of absolute electric field distribution $|E(x,t)|$

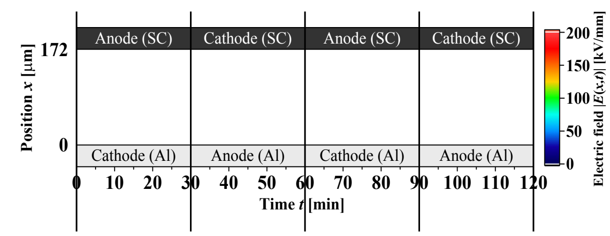


(c) Time dependence of the maximum electric field $|E_{max}(t)|$

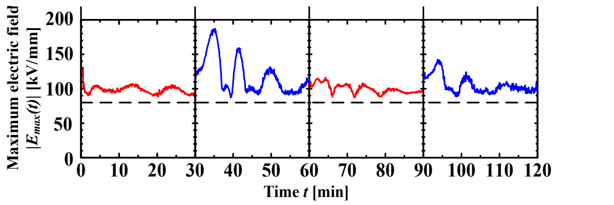
Fig. 2: Measurement results in XLPE/F under ±60 kV/mm



(a) Time dependence of space charge distribution $\rho(x,t)$



(b) Time dependence of absolute electric field distribution $|E(x,t)|$



(c) Time dependence of the maximum electric field $|E_{max}(t)|$

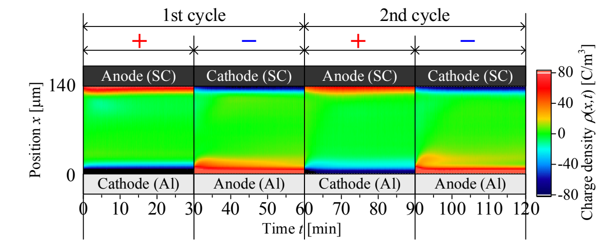
Fig. 3: Measurement results in XLPE/F under ±80 kV/mm.

reason of such packet-like charge generation can be thought that the existence of the cross-linking by-products in XLPE/F.

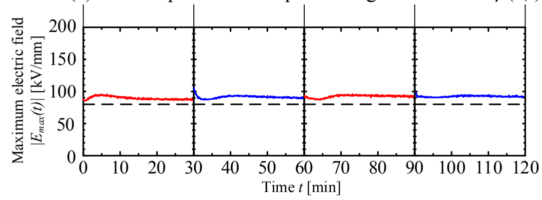
Concerning about the velocity of the packet-like charge, it seems to be getting slower with increase of the applied average stress. In our previous study [1, 2], we have revealed when the applied electric field is larger, the velocity of the injected positive packet-like charge is getting slower. The obtained results coincided with this characteristic well.

Space Charge Accumulation in DC-XLPE

Figures 4a and 4b show the time dependent space charge distribution and maximum electric field, respectively, in DC-XLPE under stress of ±80 kV/mm with the SC-Al electrode system. As shown in Fig. 3a, certain amounts (ca. 20 C/m^3) of homo space charges were observed near the both electrodes. However, any obvious space charge was not observed in the bulk of DC- XLPE. Consequently, the maximum electric field was less than 25 % of the applied electric field during the first 30 min. Even after the polarity reversal, while the electric field increased to about 100 kV/mm, it soon decreased and it became a stable at a

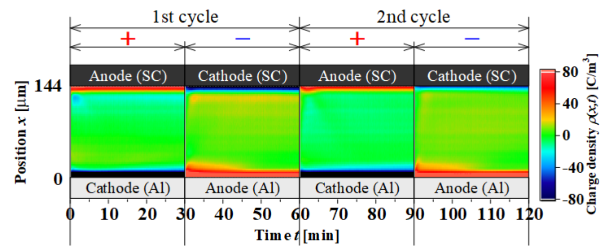


(a) Time dependence of space charge distribution $\rho(x,t)$

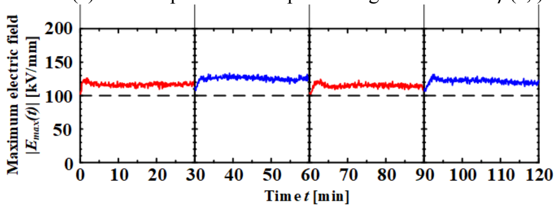


(b) Time dependence of the maximum electric field $|E_{max}(t)|$

Fig. 4: Measurement results in DC-XLPE under ±80 kV/mm.



(a) Time dependence of space charge distribution $\rho(x,t)$



(b) Time dependence of the maximum electric field $|E_{max}(t)|$

Fig. 5: Measurement results in DC-XLPE under ±100 kV/mm.

lower level. Even after the polarity reversal of ±80 kV/mm, any packet-like charge was not observed in this material. In the case of this material, the polarity reversal measurements under positive and negative 100 kV/mm were also carried out. Figures 5a and 5b show the time dependent space charge distribution and the maximum electric field, respectively. At first, a small amount of positive charge (ca. 30 C/m^3) seemed to spread through the bulk of sample as shown in Fig. 5a. Consequently, the electric field near cathode was enhanced by the space charge. However, the maximum electric field was less than 25 % of the applied electric field during the first 30 min. This increase rate is equal to that under ± 80 kV/mm as shown in Fig 4b. Even after the polarity reversal, while the electric field increased to about 130 kV/mm, it soon decreased and it became a stable at a lower level. Even after the polarity reversal of ±100 kV/mm, any packet-like charge was not observed in this material.
As mentioned about DC-XLPE in section "SAMPLES", DC-XLPE is modified XLPE and it should contain cross-linking by-products because we didn't do any degassed treatments. The material was also used for the measurement just after the removal from aluminum foil. Therefore, the DC-XLPE must have a superior property to prevent the packet-like charge injection whether it is including the cross-linking by-products or not. Anyway, it is another important thing that the material is not composed so-called nano-size filler. As we have shown in former paper, some nano-composite materials like LDPE with MgO [10] and XLPE with inorganic nano filler [9] can prevent the packet-like charge injection. However, the material used here is a cross-linked polyethylene modified with functional group/without nano materials. It means that some chemically designated materials must be available to prevent the packet-like charge injection.

Space Charge Accumulation in Sandwiched XLPE/D by Semi-Conductive Layers.

Figures 6A and 6B show the space charge characteristics in XLPE/D with SC-Al and SC-SC electrode systems under DC stress of 150 kV/mm at RT, respectively. In those figures, 6a, 6b, 6c and 6d show the time dependent space charge distribution $\rho(x,t)$, electric field distribution $E(x,t)$, external current density $J_e(t)$ and maximum electric field $E_{max}(t)$, respectively. The measurement results were obtained using a simultaneous measurement system for space charge distribution and the external current [7]. In the case with SC-Al electrode system, the current gradually and monotonically decreased with increase of the voltage application time, while that observed with SC-SC electrode system showed a peak at about 45min later after the beginning of the voltage application as shown in Fig. 6c. Judging from the space charge distributions shown in Fig. 6aA and 6aB, the peak of the current seemed to appear at the arrival of the positive packet-like charge on the counter cathode electrode in XLPE/D with SC-SC electrode system, while the injected positive packet like charge in XLPE/D with SC-Al electrode system did not reach on the cathode by the end of measurement (60 min). Consequently, the enhanced maximum electric field in XLPE/D with SC-Al was continuously increasing gradually by the end of the measurement, while that with SC-SC electrode system showed the peak just before the arrival of the packet-like charge on the cathode as shown in Fig. 6d. Furthermore, just after the arrival of the packet-like charge with SC-SC electrode system, it seemed that

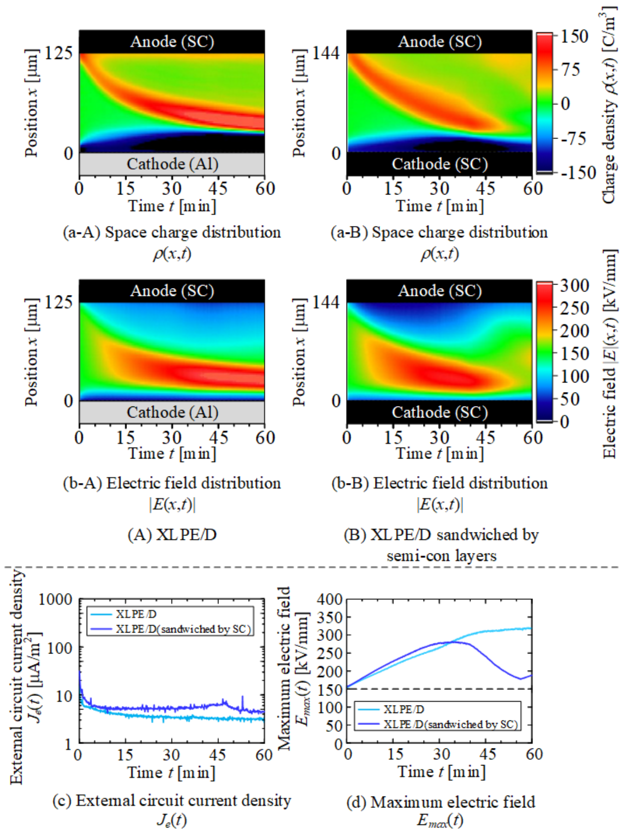


Fig. 6: Measurement results in XLPE/D and sandwiched XLPE/D by semi-conductive layers under 150 kV/mm at room temperature.

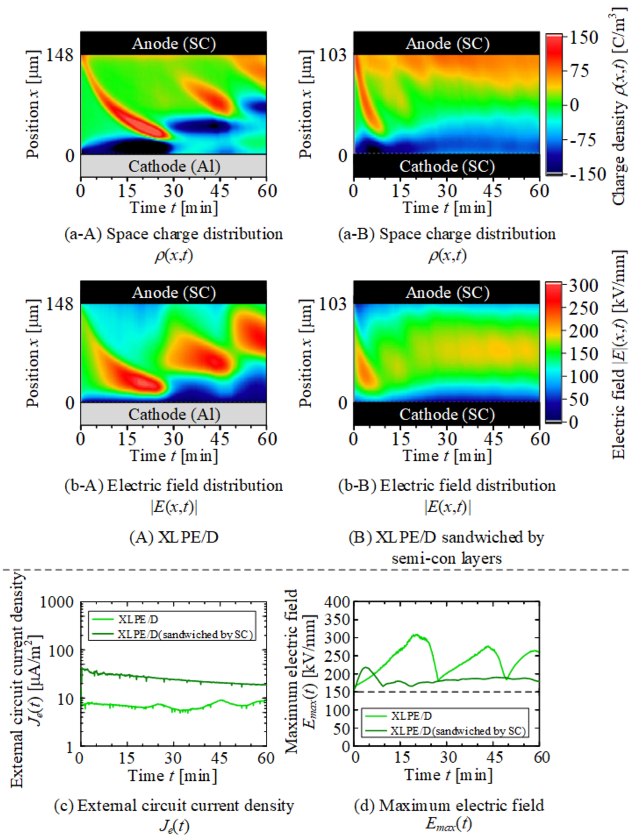
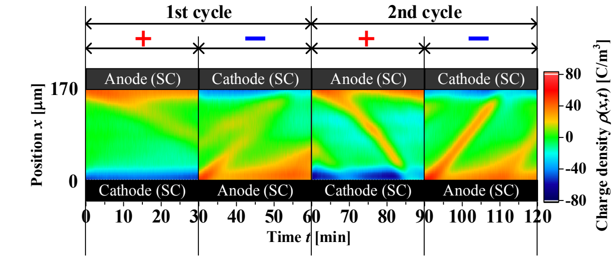


Fig. 7: Measurement results in XLPE/D and sandwiched XLPE/D by semi-conductive layers under 150 kV/mm at 40 °C.

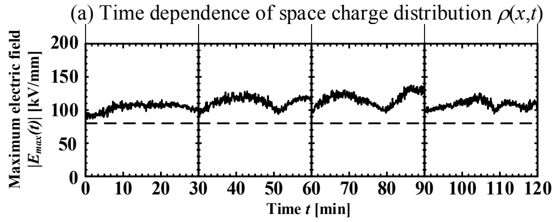
the next positive packet-like charge was generating as shown in Fig. 6aB. To show the repetition of the packet-like charge injection, we observed the space charge distribution at 40 °C. Fig. 7A and 7B show the space charge characteristics in XLPE/D under 150 kV/mm at 40 °C with the SC-Al and the SC-SC electrode systems. In these figures, Figs. 7a, 7b, 7c and 7d show the time dependent space charge distribution $\rho(x,t)$, electric field distribution $E(x,t)$, external current density $J_e(t)$ and maximum electric field $E_{max}(t)$, respectively. As shown in Fig. 7c, the time dependent external current density observed with SC-Al electrode shows the peaks, and the times of peaks seem to be the same times that the repeatedly injected positive packet-like charge reaches on the cathode electrode as shown in Fig. 7aA. In the case of that with SC-SC electrode system as shown in Fig. 7c, it is hard to distinguish any obvious peaks while the repeatedly injected packet-like charge is observed as shown in Fig. 7aB. Judging from the short repetition time of the packet-like charge with the SC-SC electrode system, a picoammeter to measure the current might not follow the such quick repetition. Anyway, as shown in Fig. 7aA, it is found that the position of the negative charge accumulation moved towards the cathode side with increase of the number of the packet-like charge injection. In the case of the SC-SC electrode system, the movement of the negative charge was not clear. However, it seemed to become closer to the anode side gradually. It can be thought that the similar phenomenon happened within short time that observed in the measurement with SC-Al electrode system. Judging from the above-mentioned results, the negative charge may be injected into XLPE/D easier from SC grounded electrode than that from Al grounded electrode. That may also be the reason why the external current was larger with SC-SC electrode system than that with SC-Al electrode system.

Space Charge Accumulation in Sandwiched XLPE/F and DC-XLPE between Semi-Conductive Layers at Polarity Reversal

Figures 8a and 8b show the time dependent space charge distribution and maximum electric field, respectively, in XLPE/F, which was sandwiched between semi-conducting electrodes, under stress of ±80 kV/mm. In this case, as shown in Figure 8a, a positive packet-like charge (ca. 10 C/m^3) was observed in the first 30 min. However, the velocity of the packet-like charge movement seemed to be slower than those observed in other experiments. Therefore, the enhanced maximum electric field also gradually increased and it reached about 110 kV/mm, which is about 38 % larger than the applied stress of 80 kV/mm, as shown in Figure 8b. After the first polarity reversal at 30 min, the larger positive packet-like charge was injected from the grounded anode electrode. The newly injected packet-like charge moved toward the cathode side as shown in Figure 8a, and the maximum electric field increased to about 125 kV/mm as the peak value, which was about 56 % larger than the applied stress of 80 kV/mm, as shown in Figure 8b. After the second polarity at 60 min, a large amount of positive packet-like charge was obviously observed and it moved across the bulk. In this term, the maximum electric field reached more than 135 kV/mm, which was about 69 % larger than the applied stress. After the third polarity reversal at 90 min, a newly positive packet-like charge was injected from the anode again, and the maximum

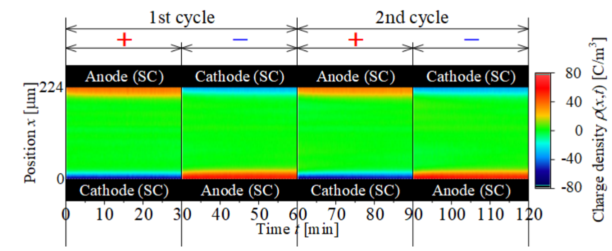


(a) Time dependence of space charge distribution $\rho(x,t)$

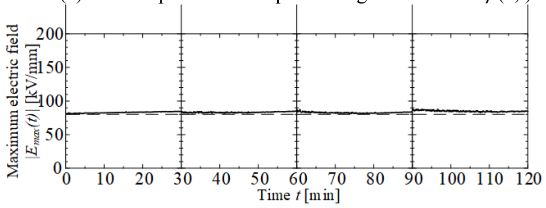


(b) Time dependence of the maximum electric field $|E_{max}(t)|$

Fig. 8: Measurement results in XLPE/F under ±80 kV/mm (sandwiched by semi-con layers).



(a) Time dependence of space charge distribution $\rho(x,t)$



(b) Time dependence of the maximum electric field $|E_{max}(t)|$

Fig. 9: Measurement results in DC-XLPE under ±80 kV/mm (Measurement by semi-con layers).

electric field also increased to about 120 kV/mm.

As shown in Figure 3, the positive charge injection was observed in the semi-conductive anode electrode under 80 kV/mm. On the other hand, obvious negative charge injection from the cathode semi-conductive electrode was not observed as shown in Figure 8. Therefore, it is natural that only obvious positive charge injection was observed in XLPE/F sandwiched by semi-conductive layers. However, as shown between 60 and 90 min in Fig. 8a, the negative charge accumulation was clearly observed in the bulk of the sample. Judging from details of the charge distribution, the negative charge injection from the grounded SC layer was observed. Therefore, the difference of the charge behaviour with SC-SC electrode system from that with the SC-Al electrode system think so the injection of the negative charge injected from the SC cathode electrode. Anyway, problem is that a larger amount of positive packet-like charge than the injected positive charge during the first 30 min was injected from the anode electrode after the polarity reversal. At the beginning of the second cycle, the amount of positive packet-like charge became larger than that observed in the first negative polarity. In other word, the positive charge gradually getting larger by passing through the

polarity reversal procedure. It seems to be saturated at the second negative polarity, however, the maximum electric field reached a very high level. While details of the mechanism should be analysed later, such positive packet-like charge generation and glow may occur even in an actual condition in XLPE cable.
Figures 9a and 9b show the time dependent space charge distribution and maximum electric field, respectively, in DC-XLPE, which was sandwiched between semi-conducting electrodes, under stress of ±80 kV/mm. In this case, as shown in Figure 9a, any obvious space charge wasn't observed in the bulk of DC-XLPE. Therefore, the maximum electric field is only 90 kV / mm at maximum when the applied electric field is ± 80 kV / mm as shown in Figure 8b. The maximum electric field of the DC-XLPE is smaller than 30% of that in XLPE/F. Judging from the above results, it can be thought that the material is applicable to the insulating material for DC cable.

CONCLUSION

Space charge accumulation in fresh XLPE (XLPE/F) and a newly developed XLPE based material for dc cable (DC-XLPE) under a sequential dc high electric stress including polarity reversal were observed using pulsed electro-acoustic (PEA) method. The accumulation of the space charge increased the local electric field significantly. Even when the semi-conducting layers were used as the electrodes, the large amount of the positive packet-like charge was observed and the electric field was enhanced significantly. It means that the usage of the normal XLPE as dc cable for HVDC system accompanied by polarity reversal may become a problem. On the other hand, when the sequential stress was applied to DC-XLPE, any obvious space charge was not observed in the bulk even after the polarity reversal, and the maximum electric field was stable with the value close to the applied electric field. This result was similar for the DC-XLPE sandwiched in the semi-conductive layer. From the result, it can be thought that the material is applicable to the insulating material for dc cable.

REFERENCES

[1] K. Matsui, Y. Tanaka, T. Takada, T. Fukao, K. Fukunaga, T. Maeno and J.M. Alison, 2005, "Space Charge Behavior in Low-density Polyethylene at Pre-breakdown", IEEE Trans. Dielectr. Electr. Insul., Vol. 12, No. 3, pp. 406-415.

[2] K. Matsui, Y. Tanaka, T. Takada and T. Maeno, 2008, "Numerical Analysis of Packet-like Charge Behavior in Low-density Polyethylene under DC Electric Field", IEEE Trans. Dielectr. Electr. Insul., Vol. 15, No. 3, pp. 841–850.

[3] Y. Li, M. Yasuda and T. Takada, 1994, "Pulsed Electroacoustic Method for Measurement of Charge Accumulation in Solid Dielectrics", IEEE Trans. DEI, Vol.1, No.2 pp.188-195.

[4] M. Mammeri, C. Laurent, M. Nedjar, 1997, "Dynamics of voltage polarity reversal as the controlling factor in space-charge induced breakdown of insulating polymers", IEEE Trans. Dielectr. Electr. Insul., Vol. 4, No. 1, pp. 44–51.

[5] IEC TS 62758, 2012, "Calibration of space charge measuring equipment based on the pulsed electroacoustic (PEA) measurement principle".

[6] Y. Tanaka, T. Fujitom, T. Kato, H. Miyake, H. Mori, S. Kikuchi, Y. Yagi, 2017, "Packet-like Charge Formation in Cable Insulating Materials at Polarity Reversal", IEEE Trans. Dielectr. Electr. Insul., Vol.24, No.3, pp.1372-1379.

[7] H. Kasuga, T. Fujitomi, H. Miyake, Y. Tanaka, 2016, "Simultaneous measurement of space charge distribution and external circuit current in XLPE under HVDC at high temperature", 2016 IEEE International Conference on Dielectrics (ICD), pp.227-230

[8] N. Hozumi, H. Suzuki, T. Okamoto, K. Watanabe and A. Watanabe, 1994, "Direct observation of time-dependent space charge profiles in XLPE cable under high electric fields", IEEE Trans. Dielectr. Electr. Insul., Vol. 1, No. 6, pp. 1068–1076.

[9] H. Harada, N. Hayashi, Y. Tanaka, T. Maeno, T. Mizuno and T. Takahashi, 2011, "Effect of Conductive Inorganic Fillers on Space Charge Accumulation Characteristics in Cross-linked Polyethylene", IEEJ Trans. FM, Vol. 131, No. 9, pp. 804-810.

[10] Y. Hayase, H. Aoyama, K. Matsui, Y. Tanaka, T. Takada and Y. Murata, 2006, "Space Charge Formation in LDPE/MgO Nano-composite Film under Ultra-high DC Electric Stress", IEEJ Trans. FM, Vol. 126, No. 11, pp. 1084-1089.