Space charge measurements and characteristics of HVDC XLPE cable

Hiroki **MORI**, Hiroshi **NIINOBE**, Yukihiro **YAGI;** VISCAS Corporation, (Japan),
h-mori@viscas.com, hi-niinobe@viscas.com, yu-yagi@viscas.com

ABSTRACT

Nowadays, HVDC extruded cables have developed. It is one of important technologies to control the behavior of space charge in insulation.

In this paper, space charge characteristics in cross-linked polyethylene (XLPE) insulation materials obtained by a lot of measurements with PEA (Pulsed Electro-Acoustic) method are reported. Furthermore, the space charge measurements were also carried out in the full size 320kV HVDC extruded cable. Consequently, the excellent performance of the specified material was verified by space charge measurements.

KEYWORDS

HVDC, XLPE cable, space charge, PEA method

INTRODUCTION

High voltage direct current (HVDC) systems are generally superior to AC systems in case of long distance transmission, because of efficiency, total cost and so on. In recent years, the demand for HVDC transmission systems has been rapidly increasing for grid interconnection, power supply to island and export from offshore wind farm. Oil filled or mass impregnated cables have been conventionally used in such application. Nowadays, extruded cables are preferred due to their advantage in load capacity, impact to environment and maintenance.

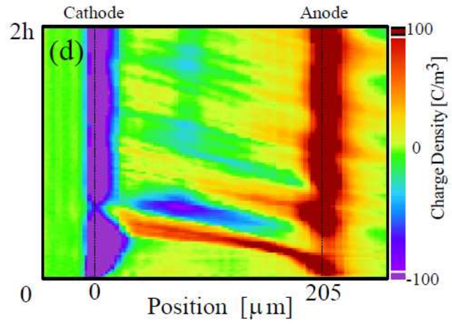
In case of extruded cables, it is known that space charges often emphasize electric field locally and cause unexpected lower performance in DC field. It is very important to understand the behavior of space charges, for example, generation, accumulation, movement and so on of them. Therefore, it is one of important technologies for development of extruded HVDC cables to control the behavior of space charges in the insulation. The behavior of space charge could be evaluated by PEA (Pulsed Electro-Acoustic) method.

Space charges accumulated drastically in insulation normally used for AC XLPE cables make DC breakdown performance lower. That is a major reason why AC XLPE cables can't be basically applied to DC application. The authors have studied that adding the special inorganic conductive filler to XLPE material could improve DC properties. The special insulation material to be suitable for DC application was named as SXL-A. This development of SXL-A was undertaken collaborative studies with Electric Power Development Co., Ltd. [1].

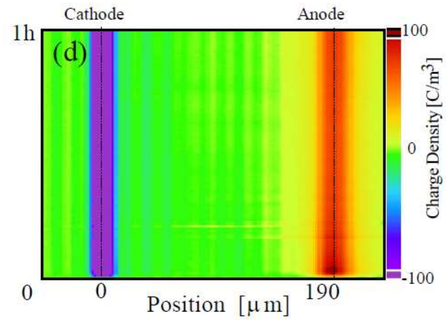
In this paper, space charge characteristics in XLPE insulation materials obtained by a lot of measurements with sheet, model cables, and full size cables are reported.

SPACE CHARGE BEHAVIOR IN XLPE MATERIALS

First of all, the short term behavior of space charge in insulation was evaluated using sheet specimens to study effectiveness with the addition of the special filler (Fig.1). The measurements of sheet specimens were undertaken in collaborative studies with Tokyo City University [2]. In the case of normal XLPE material, the space charges appeared near high voltage electrode side (Anode) at beginning stage. Then, the charges increased and moved easily toward opposite electrode side (Cathode). As the result, electric field in insulation was distorted and enhanced locally. On the other hand, in the case of SXL-A with the special filler, such space charge behavior couldn't be seen even in condition of higher electric field.



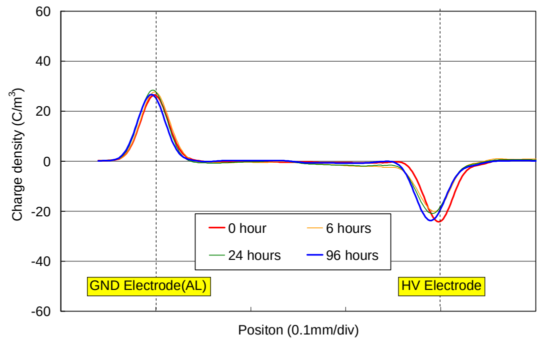
(a) XLPE (without the special filler)



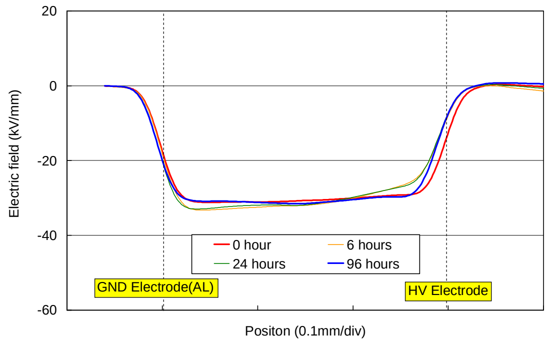
(b) SXL-A (with the special filler)

Fig.1: Space charge measurement results of sheet specimens at 200kV/mm [2]

Next, the space charge behavior in long term was also confirmed by measurements using sheet specimens. Fig.2 shows an example of the measurement results in SXL-A material. In the measurement, 30kV/mm stress was applied to the specimen in the condition of 90deg.C. The space charges had been measured from the beginning of DC voltage application to the period after 96 hours. Any space charges to make severe distortion of the field could be seen in the insulation in every period.



(a) Charge density



(b) DC electric field

Fig.2: Space charge measurement results of SXL-A sheet specimen at -30kV/mm, 90deg.C

SPACE CHARGE BEHAVIOR IN CABLE INSULATION

Space charge measurements of cable specimens are more difficult than thoes of sheet specimens because of higher DC voltage to be needed and thicker insulation of them. The procedure of space charge measurement of cable insulation and the measurement results are described below.

Procedure of space charge measurement of cable insulation

Fig.3 shows the schematic diagram of test arrangement for space charge measurement of cable specimen based on PEA method. Fig.4 shows the test loop of model cable.

The metallic shield and tapes on the cable core in the target position to be measured should be removed. PEA sensor is located at the center position of the naked cable core. The PEA sensor is attached to the surface of the outer semi-conductive layer of cable through the metal adopter. A proper pressing force on the cable helps to give enough interfacial pressure between cable surface and PEA device. The metallic screens of the cable are connected to ground at the both sides of PEA device through the resistance. This resistance also contributes as the matching impedance which helps to minimize the deflection of pulse voltage.

High voltage pulses are generated by the combination of function generator, the pulse generator and the HV pulse generator. HV pulses are applied to the cable metallic screens at both sides of PEA device. Fig.5 shows equivalent circuit on the viewpoint of pulse injection. As for capacitance, cable specimen is divided to following three portions, left side cable (C_1), right side cable (C_2) and the position on PEA device (C_s). As shown in Fig.5, when C_1 and C_2 are much larger than C_s, almost all voltage of HV pulses injected to specimen is applied to C_s.

DC high voltage induces the space charges in the cable insulation layer. High voltage pulses make the space charges excite and help the space charges to emit acoustic waves from themselves. The acoustic waves are transferred into the electric signals by PEA device. The electric signals of space charges are recorded by the oscilloscope. The obtained signals are changed to density profile of space charges at every location by using de-convolution algorithm in PC.

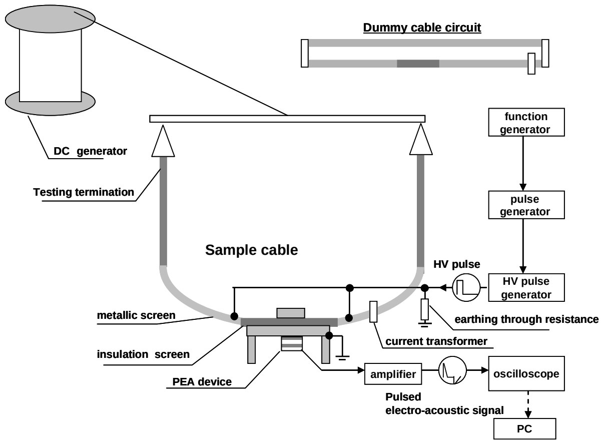


Fig.3: Schematic diagram of test arrangement for space charge measurement

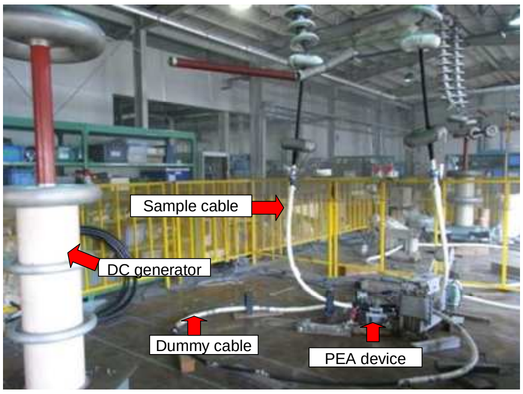
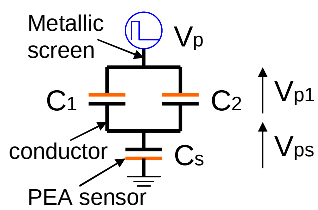


Fig.4: View of testing loop of model cable



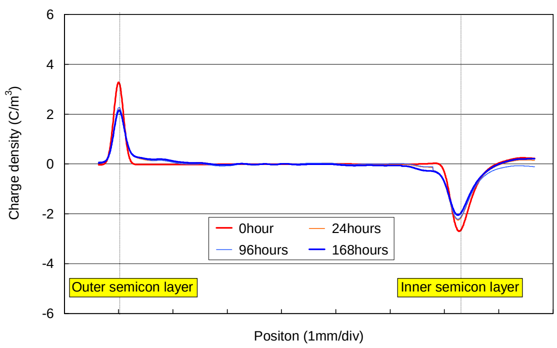
$C_1, C_2 >> C_s \quad V_{p1} << V_{ps} \fallingdotseq V_p$

Fig.5: Equivalent circuit of pulse injection

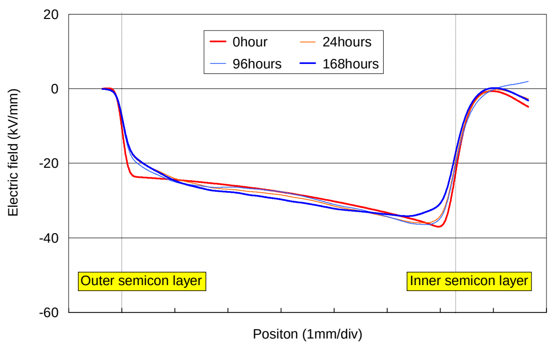
Close and Return

Space charge measurement of model cable

The model cable specimens with 6.5mm thick insulation used SXL-A material were tested under the condition of 30kV/mm and ambient temperature. The measurement results are shown in Fig.6. The homo charges appeared slightly in the insulation near not only outer semi-conductive layer but also inner semi-conductive layer. The space charge hardly increased and hardly moved for long duration. The electric field in the insulation was kept steadily without any drastic change.



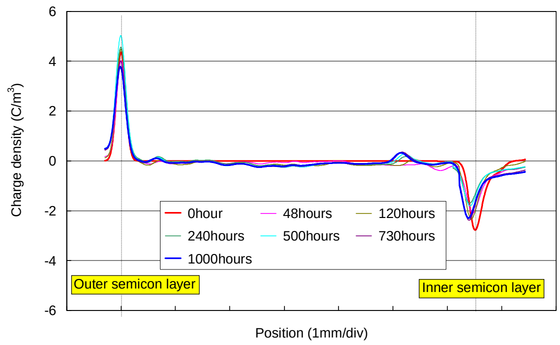
(a) Charge density



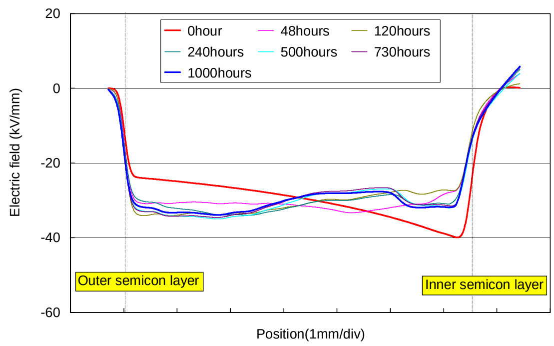
(b) DC electric field

Fig. 6: Space charge measurement results of model cable specimen at -30kV/mm, RT

Fig.7 shows the measurement results in loading condition with temperature of conductor at 90deg.C and temperature gradient of insulation at 10deg.C [3]. After voltage application, hetero charges were observed in the insulation near the outer semi-conductive layer. On the other hand, at the inner semi-conductive layer side, homo charges were observed near the semi-conductive layer and hetero charges were observed at a little inside position from the semi-conductive layer. But, any critical enhancement of electric field couldn't be seen at every location in the insulation. Fig.8 shows the change of maximum electric field in 1000hours voltage application. The maximum electric field at every period was lower than the value at beginning period.



(a) Charge density



(b) DC electric field

Fig. 7: Space charge measurement results of model cable specimen at -30kV/mm, 90deg.C

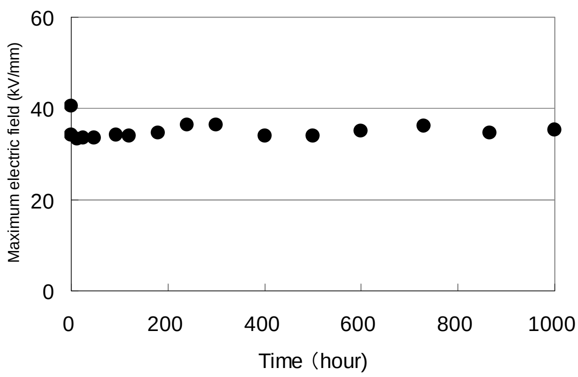


Fig. 8: Maximum electric field in insulation

In the case of LCC systems, HVDC cables are used under polarity reversal of DC voltage. The studies of DC polarity reversal were undertaken in collaborative studies with Electric Power Development Co., Ltd. [4]. The behavior of space charge in case of DC polarity reversal was evaluated with model cable. Fig.9 shows the space charge density profile just before DC polarity reversal at -45kV/mm. Hetero charges were observed near the outer semi-conductive layer. The space charge density profile just after DC polarity reversal is shown in Fig.10. The charges near the outer semi-conductive layer still stayed and behaved as homo charge just after polarity reversal as shown in Fig.10. After that, the homo charges were gradually decreasing over time and the hetero charges were observed and increasing again. Fig.11 shows the maximum electric field (E_{max}) under repetitive DC polarity reversal. The E_{max} in the measurement period could be seen every just after DC polarity reversal. The highest E_{max} was 10% higher than theoretical E_{max} in Laplace field.

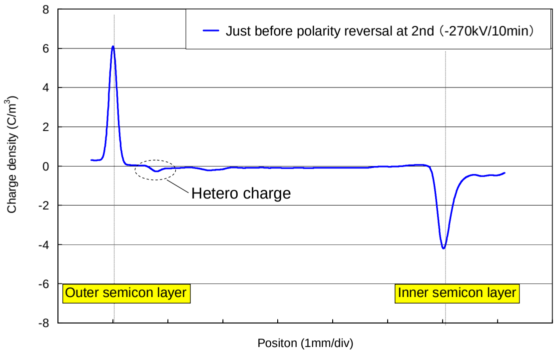


Fig. 9: Charge density just before DC polarity reversal at -45kV/mm, 90 deg.C [4]

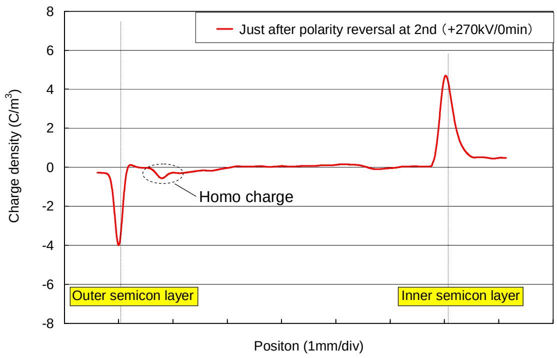


Fig. 10: Charge density just after DC polarity reversal at 45kV/mm, 90 deg.C [4]

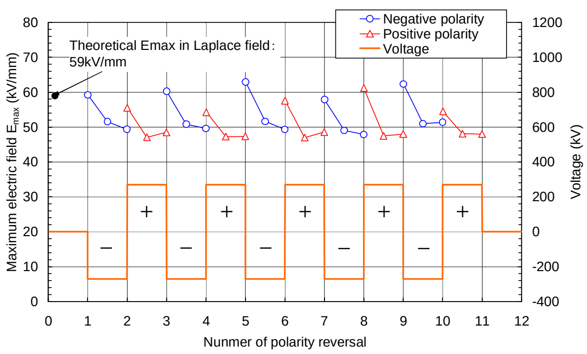


Fig. 11: Maximum electric field under repetitive DC polarity reversal [4]

FULL SIZE XLPE CABLE

The space charge measurements were also carried out in the full size 320kV HVDC extruded cable. The cables to be tested had experience of load cycle test according to CIGRE TB-496 pre-qualification test and type test [5]. Space charge measurements were the special tests not to be requested by CIGRE TB-496. Tested cable which has large size 2500mm^2 aluminum conductors, SXL-A insulation layer and smooth welded aluminum sheath is shown Fig. 12. The test conditions and space charge measurements are described below.

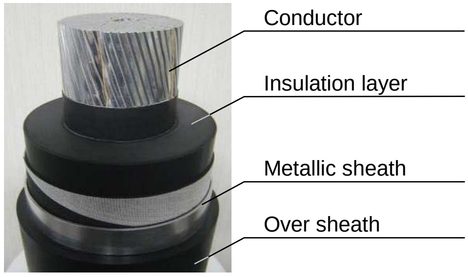


Fig. 12: 320kV HVDC cable

DC320kV prequalification test and space charge measurement

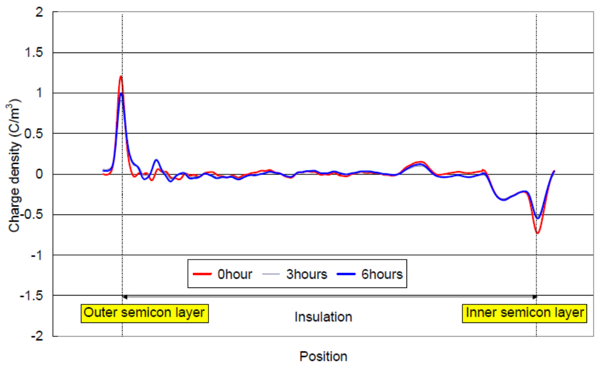
Fig.13 shows the test loop of prequalification test. The total cable length in the circuit is 190m. The test loop consisted of 4 pre-moulded joints, 2 outdoor terminations and 2 GIS terminations. The test was conducted in accordance with CIGRE TB-496 (VSC-compliant) as shown in Table 1. All of tests were successfully completed without any problem.

The cable in length of approx. 15m dismantled from the test loop was used for space charge measurement. The measurement was carried out in loading condition of 90deg.C for 6hours. Test setup and manner was same as in model cable specimens. The measurement results at negative polarity are shown in Fig.14. The behavior of space charge was almost similar to them observed in model cable specimens. It was confirmed that space charge behavior and maximum electric filed in insulation (Fig.15) were kept steadily without any severe change even after prequalification test.

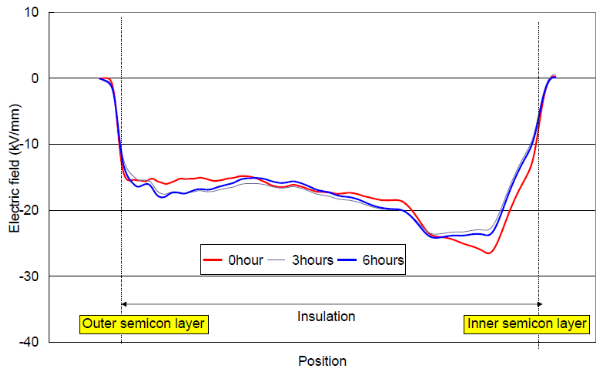
Fig. 13: View of DC320kV prequalification test loop

Table 1: 320kV prequalification test condition

No	Test Condition (U_0=320kV, T_{cond}=90deg.C)
1	LC24hours at -U_{Tp1} x 40cycles
2	LC24hours at +U_{Tp1} x 40 cycles
3	HL at -U_{Tp1} x 40days
4	HL at +U_{Tp1} x 40days
5	ZL at -U_{Tp1} x 120days
6	LC24hours at -U_{Tp1} x 40cycles
7	LC24hours at +U_{Tp1} x 40 cycles
8	±$U_{P2,S}$ S/IMP DC +/-U_0 & Simp +/-740kV (10shots)
9	±$U_{P2,O}$ S/IMP DC +/-U_0 & Simp -/+420kV (10shots)
10	±U_{P1} S/IMP DC +/-U_0 & Limp -/+780kV (10shots)
11	-U_{Tp1} x 2hours (at ambient temp.)
12	Space charge measurement ±U_0 x 6hours



(a) Charge density



(b) DC electric field

Fig. 14: Space charge measurement results of full size cable after prequalification test at -320kV

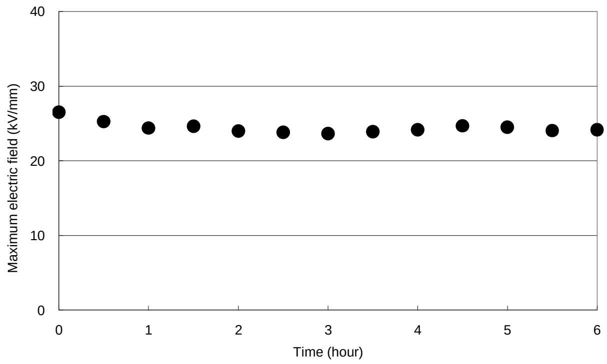


Fig. 15: Maximum electric field in insulation of full size cable after prequalification test at -320kV

DC320kV Type test and space charge measurement

Fig.16 shows the test loop of type test. The total cable length in the circuit is 60m. The test loop consisted of 2 pre-moulded joints and 2 outdoor terminations. The test was conducted in accordance with CIGRE TB-496 (VSC-compliant) as shown in Table 2. All of tests were successfully completed without any problem.

The cable in length of approx. 15m dismantled from the test loop was used for space charge measurement. Test setup and manner was same as in the prequalification test specimen. The measurement results at negative polarity are shown in Fig.17. The behavior of space charge was very similar to them observed in the prequalification test specimens. It was also confirmed that space charge behavior and maximum electric filed in insulation (Fig.18) were kept steadily without any severe change even after type test.

Table 2: 320kV type test condition

No	Test Condition (U_0=320kV, T_{cond}=90deg.C)
1	LC24hours at -U_T x 12cycles
2	LC24hours at +U_T x 12 cycles
3	LC48hours at +U_T x 3 cycles
4	±$U_{P2,S}$ S/IMP DC +/-U_0 & Simp +/-740kV (10shots)
5	±$U_{P2,O}$ S/IMP DC +/-U_0 & Simp -/+420kV (10shots)
6	±U_{P1} S/IMP DC +/-U_0 & Limp -/+780kV (10shots)
7	-U_{Tp1} x 2hours (at ambient temp.)
8	Space charge measurement ±U_0 x 6hours

Fig. 16: View of DC320kV type test loop

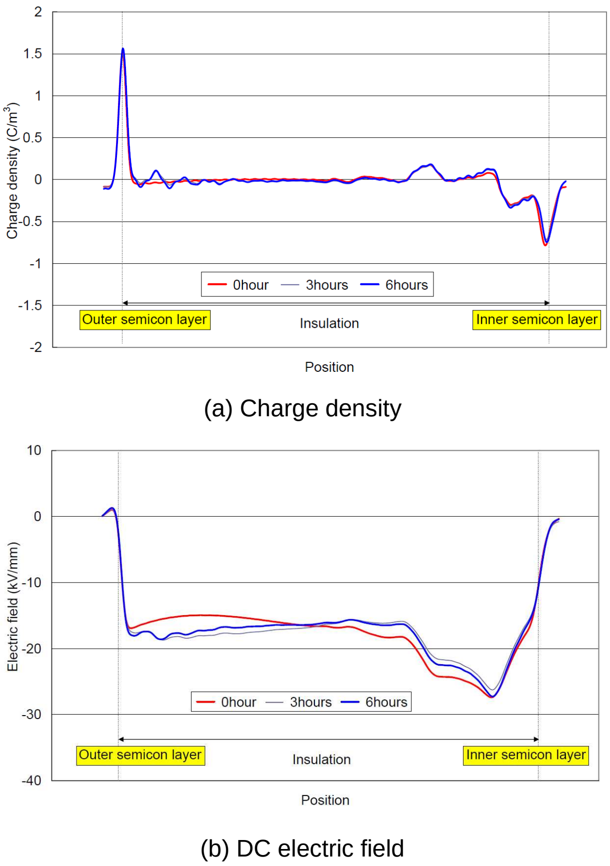


Fig. 17: Space charge measurement results of full size cable after type test at -320kV

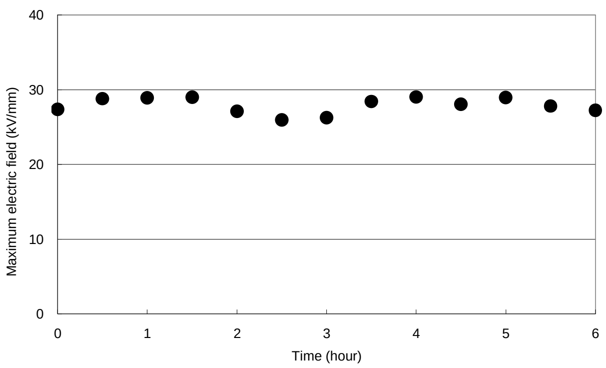


Fig. 18: Mmaximum electric field in insulation of full size cable after type test at -320kV

CONCLUSIONS

The authors reported space charge characteristics in XLPE insulation materials obtained by a lot of measurements with PEA method. First, the short term behavior of space charge in insulation was evaluated using sheet specimens to study effectiveness with the addition of the special filler. Next, the authors described test arrangements for space charge measurement of cable specimen based on PEA method. Even in some cases of loading condition of model cable specimen, it was also confirmed that the space charge measurement results were excellent.

Furthermore, the space charge measurements were also carried out in the full size 320kV HVDC XLPE cables. The cables to be tested had experience of load cycle test according to CIGRE TB-496 pre-qualification test and type test. Space charge behaviors were kept steadily without any severe change even after those tests.

PEA method which can accurately describe space charge behavior even in full size cable has been established through historical much experience. Consequently, the excellent performance of the SXL-A material was confirmed by space charge measurements. This technology is strongly expected to facilitate more worldwide application in HVDC electric field.

Acknowledgments

The authors would like to thank Electric Power Development Co., Ltd. for their support in a part of the development. At the same time, the authors also would like to thank Tokyo City University for their support in a part of the space charge measurement of sheet specimens.

REFERENCES

[1] K. Terashima, M. Asano, K. Watanabe, M. Yoshida and H. Kon, 1999, "Research and Development of DC XLPE Cable and associated factory joint", JICABLE 1999, B7.6

[2] T. Mizuno, T. Takahashi, H. Harada, N.Hayashi, Y. Tanaka and T. Maeno, 2011, "Effect of conductive inorganic filler on space charge characteristics in XLPE as a HVDC insulation material", JICABLE 2011, C.5.2

[3] H. Niinobe, N. Ishii, T. Nakajima, A. Watanabe, H. Tanaka and H. Kon, 2012, "Advanced technology for reliable HVDC extruded cable system", Cigre Colloquium San Francisco, B1-9

[4] K. Takayanagi, T. Shinozaki, H. Mori and H. Niinobe, 2013, "DC Polarity Reversal Characteristics of HVDC Insulation Material", 2013 Annual Conference of Power and Energy Society IEE Japan, No.300 (in Japanese)

[5] Y. Yagi, H. Niinobe, H. Kon, H. Tanaka, A. Watanabe and T. Nakajima, 2013, "Advanced technology for reliable HVDC extruded cable system", 18th International Symposium on High Voltage Engineering, PH-12