DEVELOPMENT OF A 270 kV XLPE CABLE SYSTEM FOR HVDC APPLICATION

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ABSTRACT

A type test qualification has been performed on a full cable system, including a 1000 mm² aluminium conductor cable with 17 mm insulation thickness and accessories (moulded field joint and terminations). The joint used during the test campaign took advantage from the LDPE experience gained on the EHV 225 kV AC networks.

The test was carried out on a 270 kV system according LCC converter type protocol of CIGRE recommendations TB 219. The cable system passed successfully and allows to a qualification for both technologies VSC and LCC.

The authors will present the main characteristics of the system in test, and details the results obtained

KEYWORDS

Space charge, XLPE, PEA, VSC, LCC.

INTRODUCTION

Today, DC seems more suitable than AC for long length high voltage power transmission. Indeed, multiple losses such as capacitive loss encountered in AC can be drastically reduced by working in DC [1]. Using polymers as insulation for HVDC cable is a challenge for a number of researchers and manufacturers due to the multiple advantages brought over current oil-filled paper insulation.

There are, however two main reasons why the traditional paper type cable has been used for transmission of energy for DC application.

The first one is a fairly restricted market dominated by paper insulation that fit in satisfactorily with the need. Thus the profitability of the investments required to developed synthetic insulation HVDC cable was not proved. The second one is related to the only technical point of view due to the insufficient knowledge of the extruded synthetic material's behaviour under DC stress. Space charges formation under DC stress is certainly the major concern for such a material. The space charges build up may modify the electric field distribution inside the insulation and leads to local overstresses unsuitable to long-run ability. In addition the introduction of VSC technology where the power flow reversal occurs without changing polarity of the cable encourages the use of synthetic insulated cables.

During last years many progress for semi-conductive and insulation polymeric materials were done and insulation technology was significantly improved as well.

Sileccable started the study to develop materials and technology for extruded insulation cables in years'90s [2]. Measurement techniques are now available and the spatial distribution of space charge was deeply investigated, applying PEA technology (Pulsed Electro-acoustic Analysis).

The intention of the present study is to explore the possibility to use plaques and model cable for characterisation of the dc electrical properties. The focus of the paper is to asses the reliability of XLPE insulation cable system subjected to high dc electric stress with polarity reversal. This paper describes the development process of 270 DC XLPE Cable systems with the results of the type tests qualification according Cigre recommendations TB 219.

EXPERIMENTAL

PEA system for plaque samples

Space charge measurements have been performed using the Pulsed Electro-Acoustic (PEA) method. The method consists in detecting and analyzing the acoustic waves generated by the interaction between the space charge in the material and an applied electric pulse. Further information about the technique is given in [3, 4]. The test bench set up is given in fig. 1

Fig.1: PEA Test bench for plaque specimen up to 30 kV

The samples were submitted to dc poling voltages in the range 5 to 20 kV, corresponding approximately to applied fields 10 to 40 kV/mm. A polarity reversal is performed after the step of 40 kV/mm.

Voltage ramp-up and ramp-down were 1 kV/mm/s. Data

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acquisitions were performed only when the voltage is stabilized (not during the ramps). PEA profiles were recorded regularly during the poling lasting for 3h at each voltage step (including volt-off measurement) followed by a depolarization period with the sample grounded. Fast data acquisition (1 profile every 5 seconds) is performed at the beginning of each polarization or depolarization step.

Polarization / depolarization cycles, as depicted in Fig. 2, were applied consecutively on the same sample.

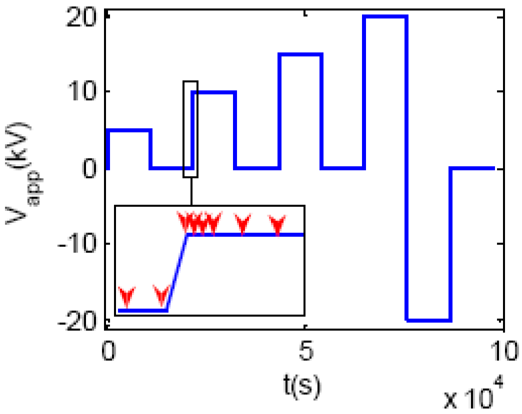

Fig. 2 : Applied voltage protocol for an insulation with a thickness of 500µm and acquisition procedure illustration. Each voltage step lasts for 3h.

PEA Space charge characteristics on model cable

The pulsed acoustic method has been investigated to measure space charge distribution on three layers model cable with insulation 4,5 mm. A 50 mm² copper conductor was used in this cable. The model cable was submitted to DC poling voltage of negative 80 kV corresponding to, approximately 25 kV/mm electric field at conductor screen. The conductor was heated to 70°C. The space charges profiles were recorded during the poling lasting for 5400 s followed by a depolarization period lasting 1800 s. The test bench set up is given in fig. 3.

Fig.3: Test bench up to 100kV DC for cable model

RESULTS AND DISCUSSION

Space charge results for plaque samples

Plaques of XLPE with a thickness of about 500 µm are obtained by crosslinking the blend at 180°C for 15 min under a press. Then fresh XLPE samples are degassed at 50°C for 3 days to remove high boiling point by-product residues. Finally, gold electrodes are deposited onto the samples by sputtering.

The effect of degassing is illustrated in Fig. 4 in case of degassed and non-degassed XLPE. FTIR analysis shows that an important proportion of acetophenone and cumyl alcohol can be removed by degassing the sample for 2 days at 50°C.

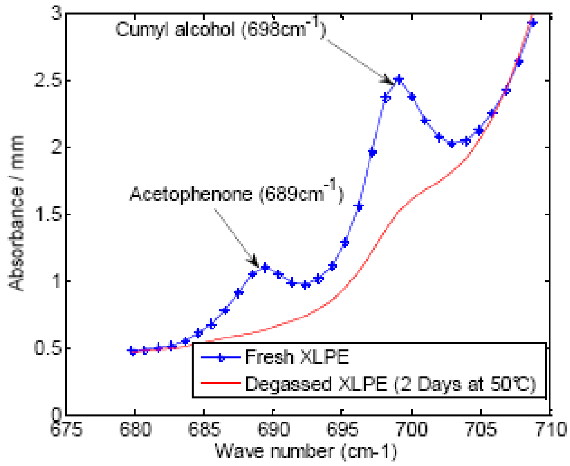

Fig. 4: FTIR spectrum of degassed and non-degassed XLP samples cross-linked.

For 10 and 20 kV/mm, positive charges are accumulated in the bulk of the insulation and positive heterocharges are observed adjacent to the cathode (see Fig. 5). This kind of space charge distribution suggests that electric field is enhanced at the cathode and relaxed at the anode. Furthermore, these charges seem deeply trapped as an important quantity of the original charges. Negative charges close to the anode are no more observed, these could be neutralised by some positive injected charges at the anode.

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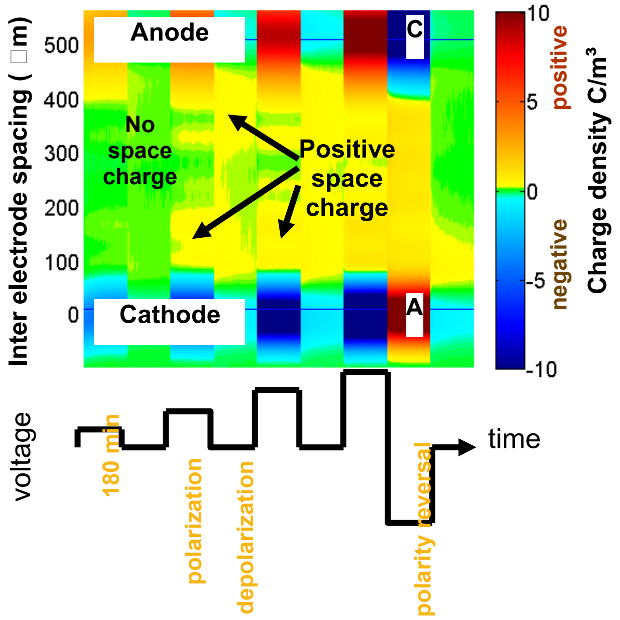

Fig. 5: Spatial distribution of Space charge in plaque samples during the poling and depolarization, respectively.

- Positive space charge accumulation in the bulk of the material
- Electric field enhancement at the cathode and field relaxation at the anode.

It has been found useful to combine the spatial distribution of space charge to the measurement of a parameter known as Field enhancement factor (FEF). FEF is defined as a ratio of the field at a given location with and without space charge.

A material with FEF=1 is the preferred choice for DC application. In case of heterocharges accumulation close to the electrode, the electric field will be higher than the Laplace field resulting in FEF values > 1.

The FEF evolution given in fig. 6 is a result of the space charge cartography shown in fig. 4. The positive space charge increases the field at the cathode at each voltage step inducing FEF>1. On the other side, the positive homo-space charges decrease the field at the anode at each voltage step allowing to FEF<1.

A strong field enhancement at the cathode is recorded upon polarity reversal, due to the positive space charge previously accumulated in the bulk. After the polarity reversal, a positive bulk charge is gradually building up close to the cathode. This phenomenon, referred to as "mirror charge effect", has been reported by different authors [5, 6]. In parallel, a strong field reduction at the anode occurs upon polarity reversal, due to the positive space charge previously accumulated in the bulk.

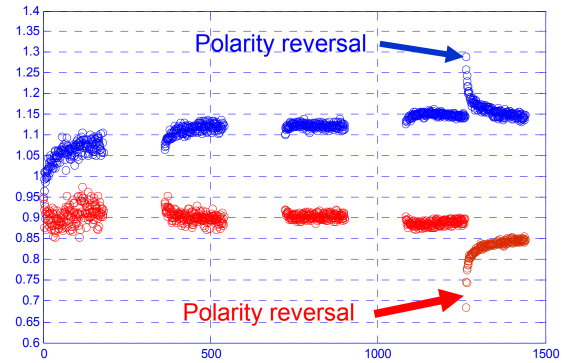

Fig. 6: FEF evolution in plaque samples during the poling and polarity reversal, respectively.

- FEF >1 at the cathode during the poling
- FEF <1 at the anode during the poling
- Strong field enhancement at the cathode upon polarity reversal
- Strong field reduction at the anode upon polarity reversal

To provide an estimate of the kinetics of trapped charges release, we have considered the time evolution of the space averaged charge density, taken in absolute value, during the depolarization phase.

According to Fig. 7, trapped charges are released very slowly, that could be due to the presence of deep level traps within the insulation. However, the nature of these traps is unknown (whether it is structural or chemical).

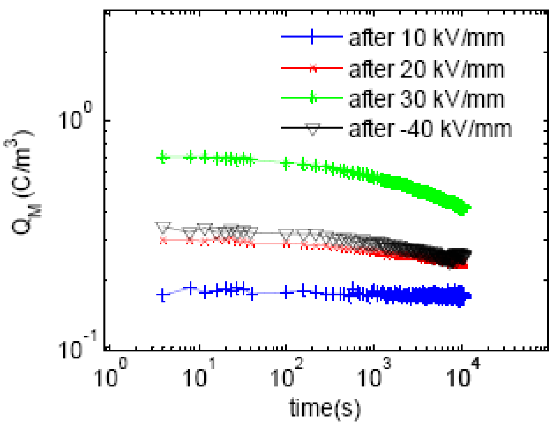

Fig. 7: Decay of the volume-averaged trapped charges density after different voltage stress in XLPE.

B. Space charge results for model cable

Comparative space charge measurements in model cable were carried out at 25 kV/mm when the conductor was heated at 20°C and 70°C respectively. The horizontal axis in the graph shows the distance in mm from the inner to the outer semi conductive layer.

Space charge profiles realised during poling indicates that hetero-space charge is accumulated at the anode as well as at the cathode Fig.8

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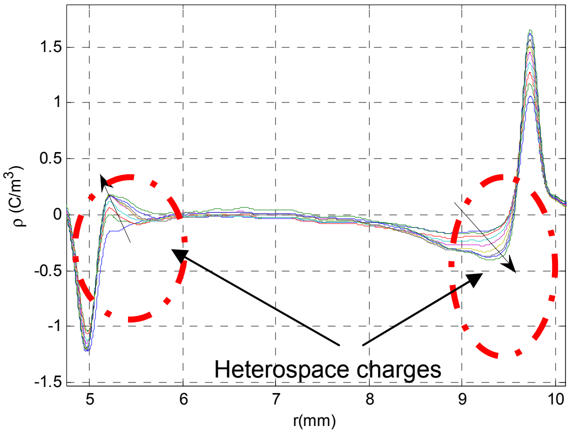

Fig. 8: Voltage-on space charge density in model cable poled at 25 kV/mm at 20°C

Fig. 9 shows a spatial space charge distribution in presence of gradient of temperature during the depolarization period. Negative hetero space charge is observed at the anode (external electrode) only. The electric field is enhanced inducing FEF>1. The accumulated hetero-space charge disappears at the cathode (inner electrode).

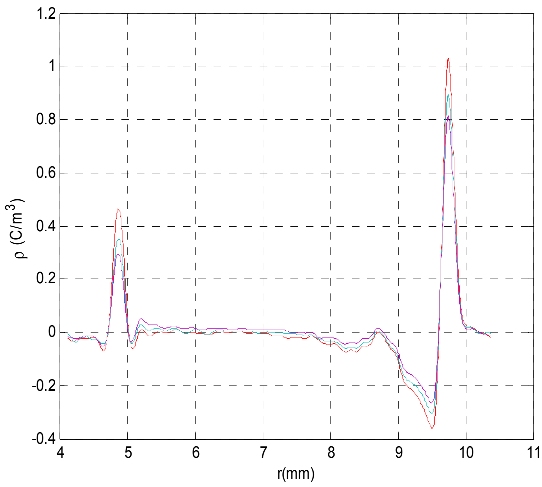

Fig. 9: Space charge density in model cable with gradient of temperature during the polarization period

FULL SIZE SYSTEM

Electrical withstand of model cable

The use of extruded insulation cables in the HVDC links showed a large increase during last years, due to some advantages that polymeric insulation can offer in comparison to traditional laminated. Despite to these advantages, development of extruded cables application for HVDC was hampered by sensitivity for the cables to polarity reversal. This was generally attributed to the presence of space charge trapped within cable insulation.

Silec Cable has developed and tested in the early 90's a solution for LCC based on Low Density Polyethylene.

The knowledge acquired during previous years gave us confidence about use of extruded cables also with polarity reversals. In the second part of the study, model cables having 50 mm² copper conductors, with 4.5 mm of insulation thickness were produced and submitted to an extensive test program.

- d.c. dielectric strength,
- Lightning Impulses test
- HVDC life test with thermal cycles at 95°C with polarity reversals.

Tests	kV/mm
Average d.c.dielectric strength (polarity -)	67
Light Impulses test - polarity + - polarity -	 182 > 130*

*: value limited by laboratory termination withstand

Table 1: Mean breakdown gradient on model cable

Different semi-conductive and insulation polymeric materials were submitted to HVDC life tests with thermal cycles at 95°C with polarity reversals. The duration tests reached 60 heating cycles with 60 polarity reversals under a mean gradient of 30 kV/mm. No breakdown or flashover was detected during the tests.

Qualification of a 270 kV cable system

In the third part of the project, the best combination of the complex semi-conductive and insulating materials was used to produce a full-size, 1000 mm² aluminium conductor cable with 17 mm insulation thickness.

The terminations are entirely synthetic. They are fitted with elastomeric sheds, a deflecting cone and a linear voltage distribution device. The joint is the trickiest part to develop. Regarding to space charges behaviour, a special emphasis is given to the moulded field joint (Fig.10). Moulded joints avoid the problems of interfaces and can be of the same diameter than the cable. Indeed, the technique of rebuilding of the joint is based on the use of the same insulation as the cable. This confers to the moulded joint a great homogeneity, avoiding the problems of interface harmful to a good behaviour under D.C. current.

Fig. 10: 270 HVDC moulded joint

The tested joints during the test campaign were rigorously identical to those installed on the EHV 225kV AC networks, for which the technique of manufacture had been previously developed (1500 in service worldwide)

These joints (Fig. 11) are adapted to 225kV AC applications therefore they have an intrinsic basic impulse level higher than 1050kV. It is noted that in the case of return of experience field, an examination with EDF of a 225 kV AC moulded joint installed in 1975 (Perret Baudry link) didn't reveal any signs of deterioration.

Fig. 11: 225 kV AC moulded joint

The type test qualification of the HVDC cable system on the 270 kV level is focused on LCC (Line Commutated Converter) converter type, where polarity reversals were applied during heat cycling.

The cable systems consisting of a length of approximately 45 m of cable 1000 mm² Aluminium XLPE (17 mm thick) equipped with a moulded field joint and two outdoor type terminations see Figure 12

Fig. 12: Type test set-up for 270 kV LCC cable systems

The cable and relevant accessories (moulded field joint and terminations) was submitted to the complete qualification according LCC protocol in accordance with Cigre Technical brochure N° 219 [7]. The type test was conducted for a nominal voltage of U_0 = 270 kV.

It is underlined that a cable system qualified according to this recommendation for use with LCC is also qualified for use with VSC (Voltage Source Converter), but not the opposite.

The Electrical Type Tests are performed as the following:

- Bending test according IEC 60840
- Load Cycling (successful tests)

8 cycles at 1.85 x 270 = -500 kV, 8/16 h heating /cooling

8 cycles at 1.85 x 270 = +500 kV, 8/16 h heating / cooling

8 cycles with polarity reversal at 1.45 x 270 = 392 kV, 8/16 h heating /cooling

3 cycles at 1.85 x 270 = +500 kV, (24/24 h heating /cooling)

- Superimposed surge voltage test:

•Udc = +270 kV, Up2o = -380 kV, 10 times

•Udc = -270 kV, Up2o = +380 kV, 10 times

- Superimposed Lightning Impulse Withstand Test:

•Udc = +270 kV, Up1 = -450 kV, 10 times

•Udc = -270 kV, Up1 = +450 kV, 10 times

- Subsequent DC test:

•Udc = - 420 kV, 23 h

All the tests mentioned under the test programme above have been successfully performed and the results obtained related to the work ordered and the materials tested are satisfactory.

Additional performance tests focused on Superimposed Lightning impulse withstand tests for a nominal voltage U_0 = 320 kV were carried out on the same cable system loop.

- Superimposed Lightning Impulse Withstand Test:

•Udc = +320 kV, Up1 = +665 kV, 10 times

•Udc = +320 kV, Up1 = - 375 kV, 10 times

•Udc = -320 kV, Up1 = +375 kV, 10 times

•Udc = -320 kV, Up1 = -665 kV, 10 times

The cable system passed the tests successfully.

Otherwise, a type test qualification for 2500 mm² copper cable systems including two moulded joints and composite outdoor terminations is currently in progress. The test is conducted according VSC protocol of Cigre recommendation for a nominal voltage U_0 = 320 kV see Figure. 13.

Fig. 13: Type test set-up of the 320 kV cable systems

CONCLUSION

Space charge measurements have been investigated on plaques samples and three layers model cable. Space charge profiles in presence of gradient of temperature shows a negative space charge accumulation at the external electrode. The electric field is enhanced inducing FEF>1. It seems that positive hetero-space charge disappears at the inner electrode.

Model cables having 50 mm² copper conductors, with 4.5 mm of XLPE insulation thickness were produced and submitted to an extensive test protocol.

Successful completion of full type test qualification has been performed on a 270 kV cable system, according LCC converter type, where polarity reversals were applied during heat cycling. The test was conducted according to CIGRE recommendations TB 219.

It has been confirmed that the moulded joint withstand the electrical stress during reversal polarity. Indeed the space charges accumulation leads to electrical field enhancement at each cycle. The technique of rebuilding of the joint is based on the use of the same insulation as the cable. This confers to the moulded joint a great homogeneity, avoiding the problems of interface, harmful to a good behaviour under D.C. current.

The cable system passed successfully and allows to a qualification for both technologies LCC and then for VSC converter type.

A type test qualification for 2500 mm² copper cable systems including two moulded joints and composite outdoor terminations is currently in progress. The test is conducted according VSC protocol of Cigre recommendation for a nominal voltage U_0 = 320 kV.

The knowledge gained during previous years combined with the results obtained gave us confidence about use of extruded cables for HVDC power transmission. A 400 kV system should not raise particular points with a mean electrical field of 20 kV/mm inside the main insulation.

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