345kV DC XLPE Extruded Cable Systems Development

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ABSTRACT

The recent projects in HVDC underground link have led to use the extruded cable combined with the VSC converter technology.

This study describes the DC extruded cable systems development for voltage level ranging from 270kV up to 320kV. In addition, the authors explore the reliability of the cable systems up to 345 kV where the tests of qualification have performed according to both VSC and LCC technology.

The behaviours of space charge accumulation of the main insulation system for cable and premoulded accessories under DC stresses have been investigated.

This paper describes the development process DC XLPE cable systems with the results of an extensive performance tests qualification.

KEYWORDS

HVDC, XLPE, Space charge, VSC, LCC, CIGRE TB 496.

INTRODUCTION

For many years, there is a strong attraction in the used of submarine and underground for high voltage direct current (HVDC) cables. This request involves the cable and accessories qualification whose voltage level rises gradually with market demand. The choice of extruded cable reinforces this growing interest in achieving high voltage links without maintenance and low impact for environment [1].

General Cable has started DC study on 270 kV extruded cable systems in 90's [2]. The knowledge acquired during previous years gave us confidence about use of cross-linked extruded cables with polarity reversals. The type test qualification of the HVDC cross-linking based cable system on the 270 kV level is focused on LCC (Line Commutated Converter) converter type, where polarity reversals were applied during heat cycling [3].

Such strategy has been continuing to reach the voltage level ranging from 320 kV up to 345 kV. The DC development approach has been articulated on the assessment of the cross-linking based cable system and better understanding of space charge behavior in those materials 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 and both long submarine and underground links are being considered and actively implemented.

In this paper the behaviour of the space charge accumulation in XLPE cable and EPDM as main insulation for premoulded accessories under DC stresses has been investigated. Measurement techniques are now available and the spatial distribution of space charge was deeply investigated, applying PEA (Pulsed Electro Acoustic) technology. Further information about the technique is given in [4, 5].

In this study both premoulded and extruded moulded jointing technology to the HVDC system has been demonstrated. The concept of premoulded joints has several attractive features including the ability to fully test before installation. In contrast extrusion moulded joints offer an important route to ensuring compatibility of the jointing and cable materials and offer a long term prospect of systems with the highest reliability. In parallel this paper introduces the newest technology based on the development of the premoulded joint which has sufficient reliability for currently envisioned HVDC systems.

The focus of the paper is to assess the reliability of XLPE insulation cable system equipped with moulded field joint and premoulded joint subjected to high DC electric stress. The authors describe the development process DC XLPE cable systems with the results of the type tests qualification according to CIGRE TB 496 recommendations [6].

The electrical test has been performed with the combination of both VSC and LCC protocols.

BASIC DC PROPERTIES

DC insulation resistance and space charge properties

DC insulation resistance (ρ) properties and the space charge properties are explored on EPDM material which is the main insulating material of the premoulded accessories. The DC insulation resistance (ρ) is generally known to depend on the electric field and temperature. Its characteristics are important for the assessment of the electric field in the accessories. Figure 1 shows an example of the measurement results based on temperature dependence. The tests are conducted under an appropriate electric field where the samples are submitted to 8 hours withstand voltage conditions.

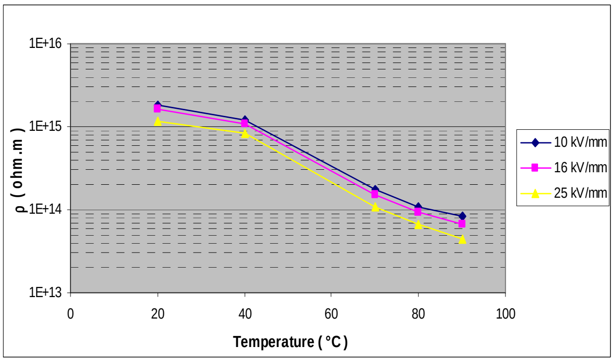

Fig. 1 : DC resistance properties of EPDM

Space charge measurements have been performed on plaques of XLPE with a thickness of about 500 µm and on model cable with insulation thickness 4,5 mm using the PEA method. It consists in detecting and analysing the acoustic waves generated by the interaction between the space charge in the material and an applied electric pulse.

The pulsed acoustic method has been also investigated to measure space charge distribution in premoulded accessories.

The samples were submitted to DC poling voltages, corresponding approximately to applied fields in the range 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 acquisitions were performed only when the voltage was 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 figure 2, were applied consecutively on the same sample.

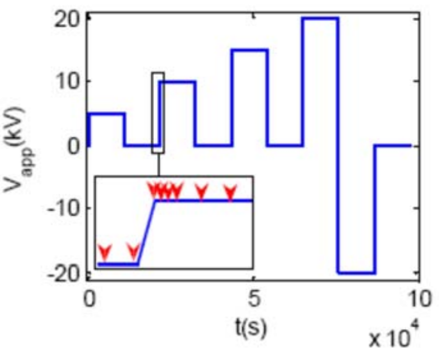

Fig. 2: Applied voltage protocol for a EPDM insulation with a thickness of 600µm and acquisition procedure illustration. Each voltage step lasts for 3h.

After 10 to 20 kV/mm poling, very little positive charges are detected in the bulk of the EPDM insulation. Few positive charges are observed at 30 kV/mm and 40 kV/mm as shown in figure 3. This kind of space charge distribution suggests that electric field is relaxed at the anode.

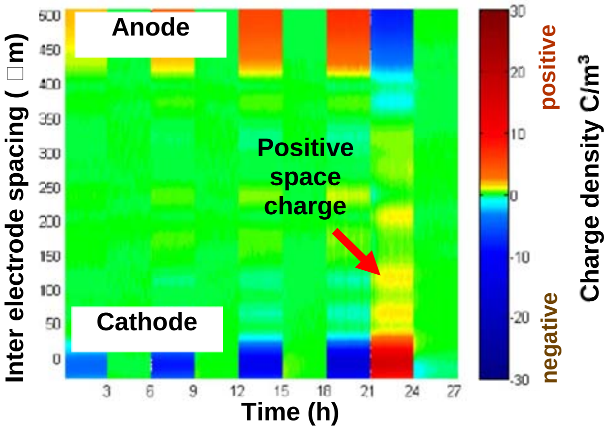

Fig. 3: Spatial distribution of Space charge in plaque of EPDM during the poling and depolarization, respectively

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 hetero-charges 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 table 1 is a result of the space charge cartography shown in figure 3. The positive space charge increases the field at the cathode at each voltage step inducing FEF>1. A strong field enhancement at the cathode is recorded upon polarity reversal and the FEF reach 1.3 approximately due to the positive space charge previously accumulated in the bulk.

Eapp(kV/mm)	10	20	30	40	-40
FEF	1.1	1.12	1.12	1.15	1.3

Table 1: FEF evolution as a result of the space charge in EPDM insulation

The evolution with time of the FEF and its location is given in the figure 4. It is observed that from 10 kV/mm up to 40 kV/mm the maximum electric field is located at the cathode. The FEF remains stable and note a slight enhancement in the range of 2%. After polarity reversal the electric field increases progressively and allows to FEF factor of 1.2 during the polling phase.

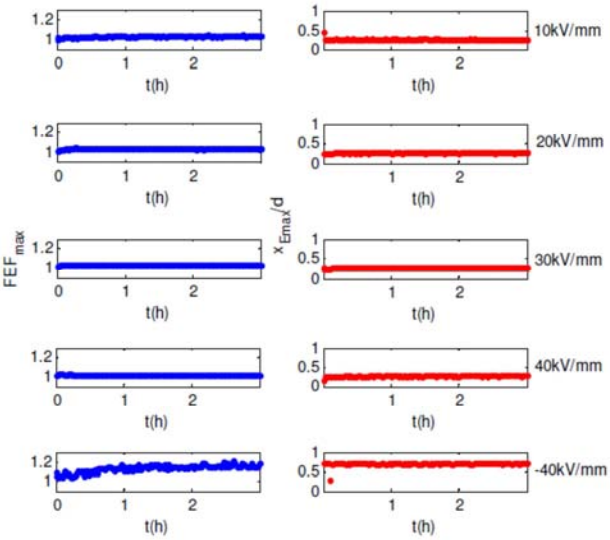

Fig. 4: Evolution of the value and the location of the FEF at different field step.
Anode at position "1" cathode at position "0" when the electric field>0

The electric field distribution in the insulating components of the accessory varies depending on the shape of electrode and the deflector that control the electric field as well as the electric field and temperature. Figure 5 plots the electric field distribution obtained by finite element calculation in the main insulating premoulded joint and its boundaries. The calculation has been conducted on 2500 mm² conductor for U_0 = 320 kV.

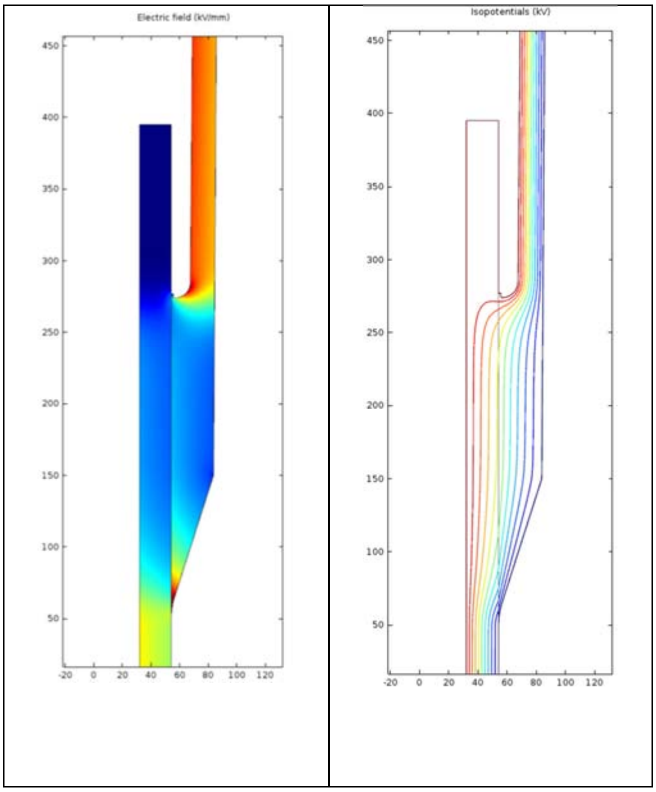

Fig. 5: Electric field distribution in premoulded joint

DEVELOPMENT CABLE SYSTEMS

VSC Qualification of a 320 kV cable system

A type test qualification for 2500 mm² copper cable systems including one moulded field joint and one premoulded joint and composite outdoor terminations has been successfully performed. The test is conducted according VSC protocol of CIGRE TB 496 recommendations for a nominal voltage U_0 = 320 kV see Figure 6.

Fig. 6: Type test set-up of the 320 DC kV cable systems

The tested moulded field joints (Figure 7) 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). Therefore they have an intrinsic basic impulse level higher than 1050kV.

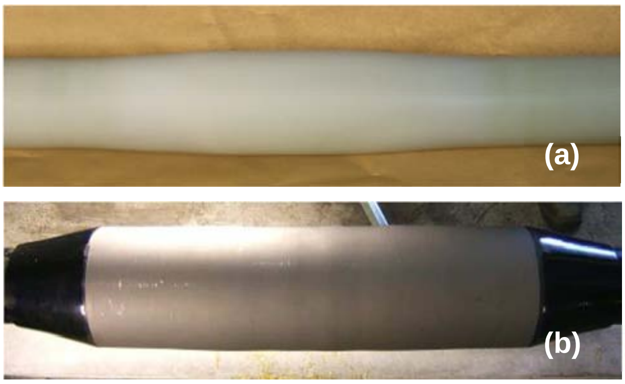

Fig. 7: 320 kV DC moulded field joint (a) and premoulded joint (b)

The electrical type tests has been performed according to the following protocol

- Bending test according IEC 62067

Load Cycle test

- 12 cycles at 1.85 x -320 = -592 kV, 8/16 h heating/cooling
- 12 cycles at 1.85 x 320 = + 592 kV, 8/16 h heating/cooling
- 3 cycles at 1.85 x 320 = +592 kV, 24/24 h heating/cooling

Superimposed surge voltage test

- U_0 = +320 kV, U_{p2s} = + 665 kV, 10 times
- U_0 = +320 kV, U_{p2o} = - 375 kV, 10 times
- U_0 = -320 kV, U_{p2o} = - 665 kV, 10 times
- U_0 = -320 kV, U_{p2o} = + 375 kV, 10 times

Lightning Impulse Withstand Test

- U_0 = +320 kV, U_{p1} = -735 kV, 10 times
- U_0 = -320 kV, U_{p1} = +735 kV, 10 times
- Subsequent DC test : U_0 = - 592 kV, 2 h

Extensive performance electrical tests

With the aim to evaluate the reliability margin, it has been decided to submit the full 320 kV DC cable systems described above (2500 mm² copper cable systems including one moulded field joint and one premoulded joint and composite outdoor terminations) to very stringent electrical tests program as illustrated in table 2.

The outstanding electrical type tests performance gave us absolute confidence about the use of suitable moulded and premoulded accessories for envisioned HVDC systems.

VSC and LCC Qualification of a 345 kV cable system

A type test qualification for 2500 mm² aluminium cable systems including premoulded joints and composite outdoor terminations has been successfully performed. The test is conducted according protocol of CIGRE TB 496 recommendations for a nominal voltage U_0 = 345 kV. The tests program combined VSC and LCC protocols.

The electrical type test has been performed according to the following protocol.

Load Cycle test

- 12 cycles at 1.85 x -345 = -640 kV, 8/16 h heating/cooling
- 12 cycles at 1.85 x 345 = + 640 kV, 8/16 h heating/cooling
- 8 cycles at 1.45 x 345 = +/-500 kV reversal polarity : 3 times/24h, 8/16 h heating/cooling
- 3 cycles at 1.85 x 345 = +640 kV, 24/24 h heating/cooling

Superimposed surge voltage test

- U_0 = +345 kV, U_{p2s} = + 640 kV, 10 times
- U_0 = +345 kV, U_{p2o} = - 440 kV, 10 times
- U_0 = -345 kV, U_{p2o} = +440 kV, 10 times
- U_0 = -345 kV, U_{p2s} = -700 kV, 10 times

Lightning Impulse Withstand Test

- U_0 = +345 kV, U_{p1} = -740 kV, 10 times
- U_0 = +345 kV, U_{p1} = +690 kV, 10 times
- U_0 = -345 kV, U_{p1} = -740 kV, 10 times
- U_0 = -345 kV, U_{p1} = +690 kV, 10 times
- Subsequent DC test : U_0 = - 640 kV, 2 h

	ZL	ZL	LC_{24}	LC_{24}	LC_{48}	SIT[1]	ZL	ZL	LC_{24}	LC_{24}	SIT[1]	LC_{24}	LC_{24}	LC_{48}	SIT[2]	LC + PR	SIT[3]	HL	HL	ZL	LC	LC	LC	LC	HL	HL
Number of cycles	1	1	12	12	3	1	1	1	5	5	1	12	12	3	1	8	1	1	1	1	20	20	8	8	40	6
Level of voltage kV	-600	+600	-600	+600	+600		-640	+640	-640	+640		-640	+640	+640		+/- 500		+640	-640	-640	+640	-640	+640	-640	+640	-640
Number of days	4	8	20	32	38	43	50	57	62	67	72	84	96	102	107	115	120	128	136	157	177	197	205	213	253	259

Table 2 : Stringent electrical tests program on 320 kV DC Cable System including both molded and premoulded joints technologies

SIT[1]	SIT[2]	SIT[3]
Superimposed Impulse and Surge Voltage Test: • Up2s = 665 kV • Up2o = 375 kV • Up1 = 735 kV UPT= - 600 kV / 2 h	Superimposed Impulse and Surge Voltage Test: • Up2s = 940 kV • Up2o = 410 kV • Up1 = 795 kV UPT = -640 kV / 2h	Superimposed Impulse and Surge Voltage Test: • UP2o = 415 KV • Up1 = 795 kV UPT = -640 kV / 2h

Pre-qualification of a 320 kV cable system

As a result of a successful completion of full type tests qualifications combined with the extensive test program results obtained on 2500mm² cable systems according to VSC and LCC protocols with nominal voltage Uo up to 345kV, it has been decided to launch one year prequalification tests. The prequalification test is performing on 2500mm² aluminum conductor with 120m approximately length of cable and including premoulded joints and two composite outdoor terminations.

The test is conducted according VSC protocol of CIGRE TB 496 recommendations for a nominal voltage U_0 = 320 kV

The test arrangement has been considered in order to simulate a representative of the installation design conditions: underground, in the tunnel and in open air.

The Prequalification electrical test is ongoing.

Figures 8 to 11 show an overview of the HVDC test laboratory and a description of the premoulded accessories subjected to the prequalification test.

Fig. 8: 320kV DC prequalification test laboratory

Fig. 9: 320kV DC outdoor terminations during the prequalification test

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Fig. 10: 320kV DC underground premoulded joint

Fig. 11: 320kV DC premoulded joint installed in tunnel

CONCLUSION

Successful completion of full type tests qualifications have been performed on 2500 mm² cable systems according to VSC and LCC protocols with nominal voltage U_0 up to 345 kV.

Space charge measurements have been investigated on the main insulation for pre moulded accessories. Space charge cartography shows a few space charge accumulations at 30 kV/mm to 40 kV/mm in the bulk of the EPDM material.

Both premoulded and extruded moulded jointing technology has been demonstrated.

The electrical type tests performance based on an extensive test program gave us absolute confidence about the use of suitable molded and premoulded accessories for envisioned HVDC systems. Based on the knowledge gained a prequalification test is launched of a full 320 kV XLPE 2500 mm² Cable Systems.

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