Influence of cross-linking by-products on electrical properties of HVDC insulating materials (Relationship between by-products, conductivity and cable dielectric breakdown)

Lazhar KEBBABI, Arnaud ALLAIS, Jean-hugues DOUMBE; Nexans Research Center, 29 rue Pré Gaudry, 69353 Lyon (France),

lazhar.kebbabi@nexans.com, arnaud.allais@nexans.com, Jean-hugues.doumbe@nexans.com

Christian FROHNE; Nexans Deutschland, Kabelkamp 20, 30179 Hannover (Germany), christian.frohne@nexans.com

ABSTRACT

This paper deals with the study of the influence of cross-linking byproducts on DC conductivity and DC field strength of HVDC XLPE materials and their consequence on HVDC cables reliability. Measurements have been carried out on three layered miniature cables. Results showed that DC conductivity of non degassed material is several orders of magnitude higher than degassed materials. It is also demonstrated that field strength of well degassed cables is around 2.5 higher than undegassed cables. From these results and knowing that cross-linking by-products concentration across full size cables section is highly inhomogeneous, we propose a simplified model explaining the possible cause of HVDC cables breakdown. It is shown that cross-linking by-products gradient induces a conductivity gradient across insulation resulting in highly field intensification and inversion near outer semiconducting layer.

KEYWORDS

HVDC, Cables, DC conductivity, XLPE, Breakdown, Crosslinking by-products.

I. INTRODUCTION

DC conductivity of XLPE is an important parameter for HVDC insulating materials where the electric field distribution across the cables as well as space charge build-up depend on conductivity. Many investigations have been performed in the past years showing the influence electric stress and temperature on DC conductivity and space charge of XLPE [1-5]. *Goshowaki et al* [6] demonstrated that Antioxidant contents and crystallinity modify significantly the conductivity of polyethylene. On the other hand, it was demonstrated that cross-linking by-products contributes to Hetero-charges built-up [7]. However, most of data available in the literature have been performed using thin plaques obtained either by molding or extrusion. In this paper we present results of DC conductivity measurements performed on three layered miniature cables in order to determine the influence of cross-linking by-products on DC conductivity of XLPE. The main advantage of using miniature cables compared to plaques consists in the relatively good stability of by-products concentration within the sample during the test. Compared to miniature cables, measurement on plate samples are characterized by the relatively small electrodes surfaces and very low wall thickness which is in the range of 100 µm. This will result in a very fast degassing during measurement that occurs within few minutes even at room temperature. Furthermore due to larger electrode surface of long length of miniature cable the accuracy of measurement of conduction current is dramatically improved. In addition, contact between electrodes and insulating material found in miniature cables is similar to full size HVDC cables since it is constituted of bounded semicon/XLPE. Knowing that interface quality has a key impact on charge carriers injection and extraction, miniature cables offer a better configuration than thin plates where metallic electrodes are generally used for conductivity measurement.

II. EXPERIMENTAL SETUP

Sample preparation

Test specimens used for the experiments are XLPE miniature cables produced for test purposes. They are constituted of solid conductor of 0.75 mm diameter, inner semiconducting layer (ø = 2.8 mm) insulating layer (ø = 5.8 mm) and outer semiconducting layer (ø = 6.1 mm) (Figure. 1). Just after production, miniature cables are stored in hermetic package and controlled temperature in order to limit degassing before the test. Degassed specimens are heat treated in oven at 60℃ during 6 days in order to remove cross-linking by-products from XLPE.

The tested sample is constituted of a coil of 30 m cable length. At each ends, the cable outer semiconductor layer is removed for certain length in order to suppress parasitic surface current. A conductive tape is wrapped around the coil, in contact with outer semiconductor layer, in order to minimize contact resistance.

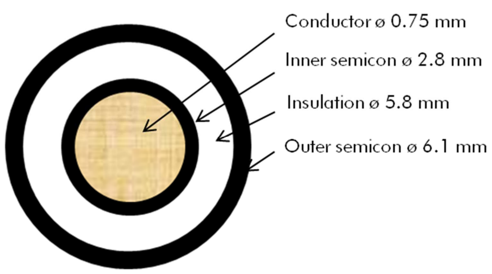

Figure. 1: Dimensions of miniature cable

Conduction current measurement

Cable sample is placed in oven for controlling temperature and relative humidity. The inner conductor of the cable is connected to high voltage output of a low ripple DC

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source and the outer conducting tape is connected to 0 V through an electrometer (Figure 2).

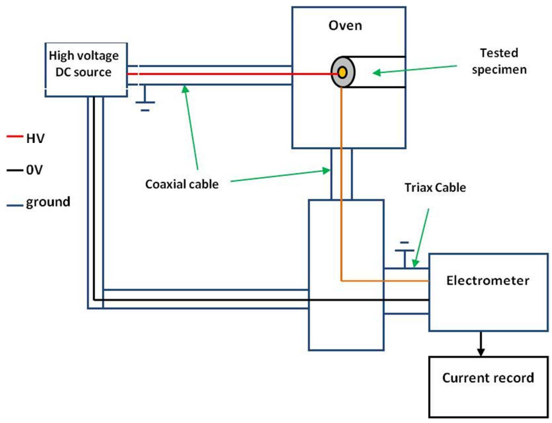

Figure 2: Schematic diagram of experimental set up for conduction current measurement

At given temperature, a stepwise increased DC voltage is applied to the sample according to diagram showed in Figure. 3. Applied DC stress is ranging from 10 kV/mm to 35 kV/mm with increments of 5 kV/mm and step duration of 4000 seconds. Currents and temperature are simultaneously recorded and stored during the test.

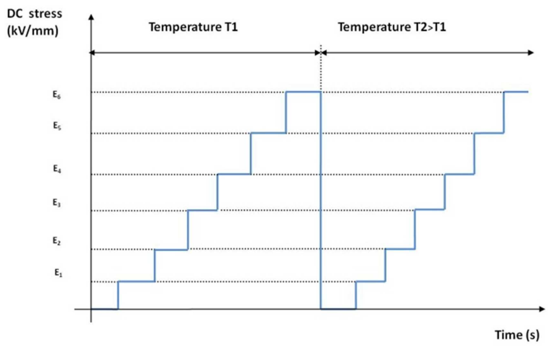

Figure. 3: Evolution of applied voltage and temperature during the test (test protocole)

III. RESULTS OF DC CONDUCTIVITY

Figure 4 showed typical current records obtained using measurement setup previously described. We observe a current decrease after voltage application and stabilisation after about 3000 seconds. The value of conduction current (current flowing through the insulation) is then considered after 3600 seconds for all our measurement. Measurement of cross-linking by-products concentration on miniature cables at 20℃ and 50℃ before and aft er conductivity measurement showed no significant variation during the test (3600 seconds) indicating that current decrease phase is unlikely to be the consequence of material conductivity change during the test, but only due to “polarisation current” decay.

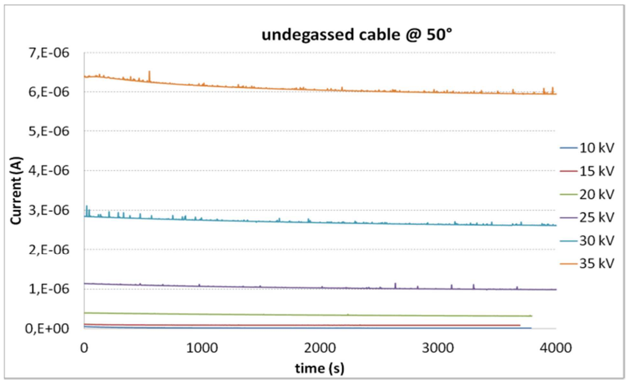

Figure 4: Example of current record i(t) obtained using undegassed cables at 50℃.

Results showed that conduction current is highly dependent on insulating material characteristics (by-products concentration) as well as applied voltage and temperature. From conduction current measurement, we calculated the insulation conductivity using formula (1) where (σ: electric conductivity, I: conduction current, r_i: inner radius of cable insulation, r_0: outer radius of cable insulation, U: Applied voltage, L: cable length)

$$\sigma = \frac{I \ln\left(\frac{r_0}{r_i}\right)}{2\pi U L} \qquad (1)$$

Figure 5 and 6 show the evolution of conductivity as function of applied field at 20℃ and 50℃ measured on degassed and undegassed samples. Results are in good accordance with the empirical law describing relationship between conductivity temperature and electric stress (equation 2) and consistant with results reported in the litterature [5].

$$\rho = \rho_0 \exp[-(\alpha T + \beta E)] \qquad (2)$$

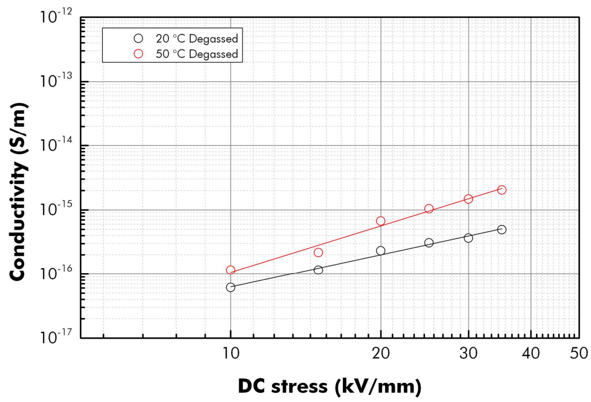

Figure 5 : Conductivity versus applied field at 20°C and 50° of degassed cables

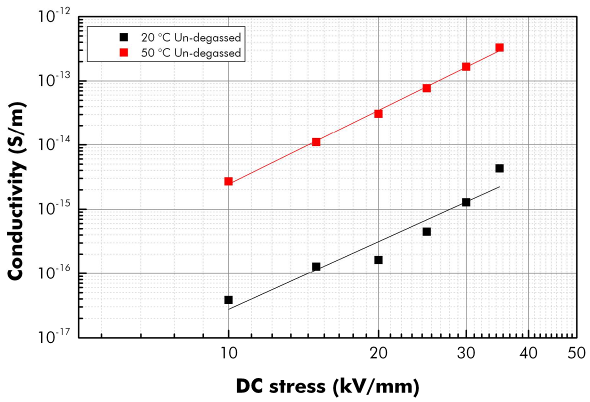

Figure 6: Conductivity versus applied field at 20°C and 50° of undegassed cables

Comparaison of results obtained at 50 °C, shown in Figure 7, indicates that conductivity of undegassed samples is significantly higher than conductivity of degassed ones. For example, $\sigma_{unegassed}$ is is 23 times higher than $\sigma_{degassed}$ at 10 kV/mm and 162 times higher at 35 kV/mm. Accordingly, all other parameters being equal, it appears that measured conductivity difference between degassed and undegasses cables is due to by-products concentration. One can conclude, that cross-linging by-products modify significaltly XLPE conductivity.

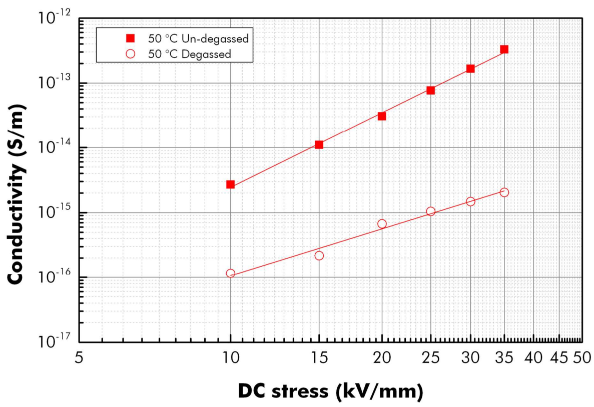

Figure 7: Comparison of cable conductivity between degassed and undegassed specimens at 50°.

IV. RESULTS OF DC BREAKDOWN TEST

DC breakdown tests are performed at room temperature using 12 miniature cable specimens of 4 m length with 1m of the outer semiconducting layer peeled on each ends Figure 8. The experimental procedure consists in testing a cable specimen at increasing DC voltage starting from 60 kV up to breakdown with increments of 20 kV and step duration of 10 seconds. For each specimen, the breakdown voltage was recorded and the data are analyzed and presented in Weibull distribution.

Breakdown tests shown in Figure 9 demonstrates that electric field strentgh of degassed cables is 2.25 times higher than undegassed ones. This results indicates that high crosslinking by-products concentration contained in undegassed cables reduces significantly DC field strength of XLPE.

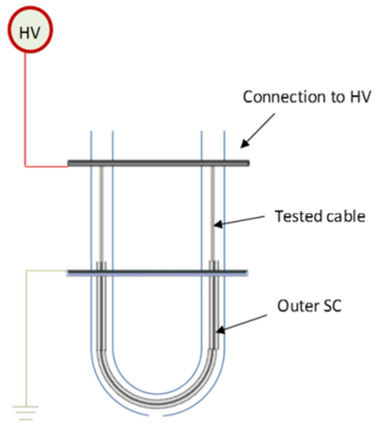

Figure 8: Schematic diagram of experimental set up for DC breakdown measurement

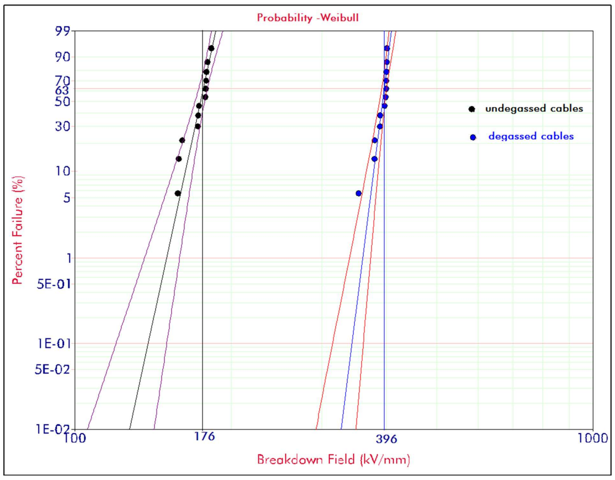

Figure 9: Breakdown filed comparaison between degasses and undegassed miniature cables

V. RELATIONSHIP BETWEEN CONDUCTIVITY, CROSSLINKING BY-PRODUCTS AND FIELD DISTORTION IN FULL SIZE HVDC CABLES

Electric field distribution in HVDC cables is determined by the insulation conductivity of the material and space charge build up. It can be shown that if the insulation resistivity were to remain constant across the insulation thickness, then the field distribution would be similar to that of an AC cable system [7]. However, if the conductivity of the insulating material is highly dependent on temperature and electric field, an electric field inversion and enhancement will occur across the cable insulation due to temperature gradient. This phenomenon is well known and conductivity of HVDC insulating materials is always expressed as function of electric field and temperature:

$$\sigma = f(T, E) \quad (3)$$

T: Temperature.

E: electric field.

The expression of conductivity as function of temperature and electric field is sufficient when the insulation material is homogeneous i.e. having the same properties in all its volume. In the case of full size HVDC cables, the concentration of cross-linking by-products is highly dependent on the position across the insulation. Depending on degassing stage of the cable different byproduct concentration profiles have been observed. On possible distribution is given in Figure 10 [8]. In this example the highest amount of by-products is located in the middle part of the insulating cross section and lowest near the outer semicon layer. This difference is due the relatively high thickness of the HVDC cables which is in the range of 20 mm. During degassing, the amount of residues decays with time, and the concentration proportion can vary.

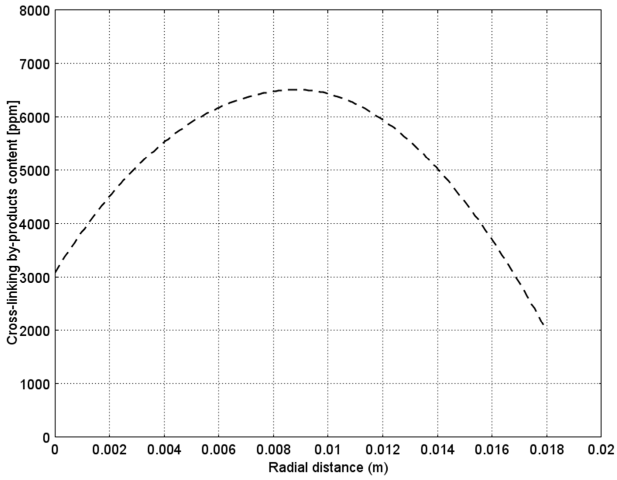

Figure 10: Crosslinking by-products concentration across cable insulation layer [8]

Taking into consideration the distribution of cross-linking by-products across HVDC cables insulation and according to conductivity measurement results, we have introduced modification the conductivity expression (equation 2) in order to simulate the electric field across the cable under DC field. Accordingly, the conductivity across of full size cable insulation can be expressed as:

$$\sigma = f(T, E, [C]) \qquad (4)$$

[C]: is cross-linking by-products concentration.

In order to demonstrate the influence of cross-linking by-products, we implemented an FEM model to simulate electric field distribution across a HVDC cable of 2500 mm² and 18 mm insulating thickness subjected to type test DC voltage of 592 kV at ambient temperature. The simulation model

was a two dimension AC/DC module of Comsol Multi-physics software. We made comparison of electric field distribution inside cable between two different cases:

1- In the case one, we consider the conductivity of insulating material as homogeneous across the cable i.e.no conductivity dependency to the by-products concentration. The conductivity is dependant only on electric field and temperature (σ =f (T, E)).
2- In the case two, we consider that the conductivity across cable is dependent on temperature, electric field and cross-linking by-products concentration (σ =f (T, E, [C])).

Figure 11 show electric field distribution variation from inner semicon to the outer semicon obtained using the simulation model. In the first case (blue line), the maximum electric field is about 40 kV/mm and located nearby the inner semicon. However, when we consider the conductivity dependency on cross-linking by-products, the maximum electric field (red line) is about 70 kV/mm and situated close to the outer semicon. This result demonstrate, that resistivity dependency on cross-linking by-products can be the root to a high field distortion and inversion inside HVDC cables and hence responsible for breakdown at relatively low field.

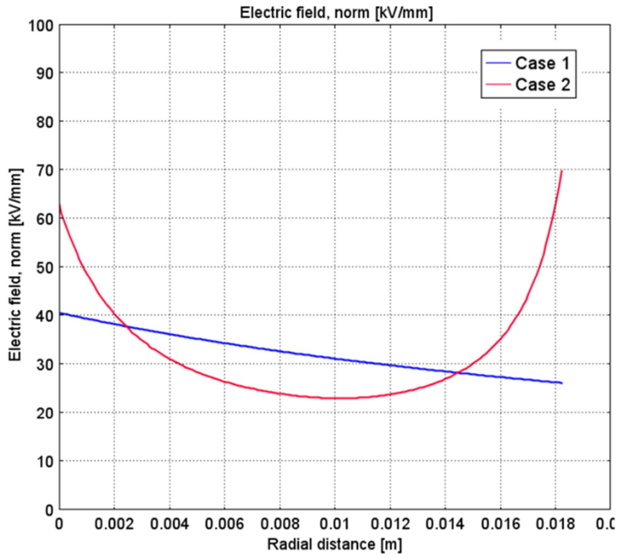

Figure 11: Simulation of electric field distribution across cable insulation layer using Comsol software: Blue line in case of homogeneous insulation. Red line when considering conductivity dependant on cross-linking by-products.

CONCLUSIONS

We have described a conductivity measurement technique based on the conduction current measurement on miniature cables. This technique allows us to investigate the influence of cross-linking by-products on XLPE conductivity. Results showed that the conductivity of degassed cables is up to 162 times higher than undegassed cables. On the other hand, DC breakdown tests demonstrate that electric field strength of degassed cables is 2.25 times higher than undegassed ones. Based on these experimental measurements and knowing that cross-linking byproducts distribution inside cables is heterogeneous and highly dependent on their position, we implemented a simplified model to calculate the resulting electric field. This model takes into consideration cross-linking by-products distribution across cable and their impact on material conductivity. Result of simulation demonstrate, that resistivity dependency on cross-linking by-products can be the root to a high field distortion and

Close and Return

inversion inside HVDC cables and hence responsible for breakdown at relatively low field.

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REFERENCES

[1] Tung TRAN ANH *et al* "Investigation of Space-Charge Build-up in Materials for HVDC Cable Insulation in Relationship with Manufacturing, Morphology and Cross-linking By-products", 2013 IEEE International Conference on Solid Dielectrics, Bologna, Italy, June 30 – July 4, 2013.

[3] M. Fu, G, Chen, L. A. Dissado, J. C. Fothergill "Influence of Thermal Treatment and Residues on Space Charge Accumulation in XLPE for DC Power Cable Application", IEEE Trans. Electr. Insul., Vol. 14, pp.53- 64, 2007.

[4] W. Choo, G. Chen and S. G. Swingler "Electric Field in Polymeric Cable due to Space Charge Accumulation under DC and Temperature Gradient" IEEE Trans. Dielectr. Electr. Insul., Vol.18, No. 2, pp. 596-606, April 2011.

[5] Aladenize B, Coelho R, Assier JC, Janah H, Mirebeau P. "Field distribution in HVDC cables: dependence on insulating materials". 4th international conference on insulated power cables (Jicable 1999), Paris, 1999.

[6] Manabu Goshowaki *et al* "Influence of antioxidants on electrical conduction in LDPE and XLPE" Journal of Electrostatics 65 (2007) 551–554.

[7] Y. Shen, "DC Cable Systems With Extruded Dielectrics" EPRI report, December, 2004.

[8] A. Smedberg, D. Wald "Determination of diffusion constants for peroxide by-products formed during the crosslinking of polyethylene" , IEEE International Symposium on electrical insulation, Vancouver, BC, pp. 586-590, Jul, 2008.