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Definition and measurement of parameters for HVDC cables and accessories

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ABSTRACT

This paper describes different measurement approach to assess the characteristics and to evaluate the main parameters of the materials used for HVDC cables and accessories application. Regarding insulation used for cables, conductivity measurements were made on plaques and on cable prototypes. For materials used in HVDC cables accessories, two different measurement approaches were compared, the measurement on plaque and the measurement on cylindrical samples. The latter shows the best and reliable results. Also FEM simulations were performed in order to evaluate the electric stress on cables and accessories with the new parameters calculated.

KEYWORDS

HVDC, Cables, Materials, Joints, Terminations.

INTRODUCTION

HVDC transmission extruded cables are becoming of more relevant importance every year. Grids are no longer national, the countries of Europe are connected, the states of the United States are connected, and the provinces of China are connected [1]. We are moving to pan-continental interconnected grid where the need of "electrical highways" is more and more important. These "highways" are the big electrical connections between countries or continents. When the connection is designed to work in HVAC, other problems can arise. Cascading failures, where a failure on one network brings down a connected network leading to a domino effect bringing down successive networks, are difficult to control on massively interconnected AC network systems, in addition, the huge capacitance of cables and hence, the reactive power absorbed, is a limit for the maximum length of the AC connection itself. These are some of the main reasons why HVDC cables are nowadays more requested and there's a lot of research in this field.

In the last years the requested power transmission capacity of the connections has drastically increased and this led to an increasing research for materials to use in HVDC power cables and accessories with always better performance in order to reach higher voltages. Of utmost importance is also the characterization of these materials in terms of electrical parameters, the better the measurements and the more reliable is the simulation and hence the choice of the appropriate materials for a new HVDC design.

In this paper, some measurement techniques used for HVDC raw material selection are reported. The first that will be discussed are relative to the insulation of the power cable, later on it will be discussed also about the accessories, that have a fundamental role for the whole HVDC system and that are the most difficult to characterize because of their non regular geometry.

MATERIALS FOR CABLE INSULATION

The insulating material of the cable is the main component to assess when a new voltage design has to be developed. For HVDC applications, however, the parameters to measure are different respect to AC applications. For AC insulation one has:

- Breakdown strength (AC, impulse)
- Permittivity
- Dissipation factor

For DC insulation they became:

- Breakdown strength (DC, impulse)
- Electrical Conductivity

In fact, while in AC the dissipation factor and the permittivity are very important due to the Laplacian and oscillating field, in DC, the steady state electric field is resistive, hence the permittivity does not play a crucial role in field grading and the conductivity take his place. The electrical conductivity is also fundamental for the evaluation of the thermal stability of insulation. Using the well known conductivity model:

$$\sigma(E,T) = \sigma_o \cdot e^{(\alpha T+\beta|E|)} \quad [1]$$

Is obvious that the electrical conductivity has a strong dependence from the temperature and the electric field.

To assess the properties of different insulating materials, measurement on plaques and prototype cables were performed. The materials tested were:

- HTPE
- XLPE

The plaques were 200x200 mm and with 0,5 mm thick. The measurements were made using a high pressure test cell shown in Fig. 1, this cell was filled with high pressure gas in order to withstand high electric fields.

Fig. 1: High pressure test cell

The cell was also equipped with a guard ring in order to exclude the border effect and to make a more accurate measurement. The cell was placed inside an oven in order to perform measurements with different voltages and different temperatures to have a full characterization of the insulating material.

The evaluation of the two insulating materials was done also on the basis of the measurement of conductivity on prototype cables. These cables are MV cables (12/20 kV) extruded using a triple extrusion head, the conductor is a 70 mm^2 aluminium and the thickness of the insulation is 5,5 mm. The measurement on cables gives the advantage to evaluate also the thermal stability of the cables and the performances of the semiconductive material used for the conductor screen and insulation screen.

A cable reel of 50 m was placed inside an oven until reach isothermal condition and the steady state current was then measured for each voltage level. Fig. 2 shows the test setup used, composed by the HVDC voltage generator, a damping resistor, two linseed oil terminations and the cable under test.

Fig. 2: Test setup used for the measurement

Using the total resistance calculated starting from voltage and current, the conductivity can be evaluated keeping into account the following relations:

$$R = \rho \cdot \int_{Ri}^{Ro} \frac{dr}{2 \cdot \pi \cdot r \cdot L} = \frac{\rho}{2 \cdot \pi \cdot L} \cdot \ln\left(\frac{Ro}{Ri}\right) \qquad [2]$$

$$\rho = \frac{2 \cdot \pi \cdot L \cdot R}{\ln\left(\frac{Ro}{Ri}\right)} \qquad [3]$$

$$\sigma = \frac{1}{\rho} \qquad [4]$$

Where Ro and Ri are respectively the outer and the inner radius of the cable and L is the length. The calculation of the conductivity was done with three voltage levels and three temperature levels in order to obtain a 3x3 square matrix filled with the conductivity values, this matrix was used then to calculate the values of the temperature coefficient α and the electric field coefficient β of the equation [1].

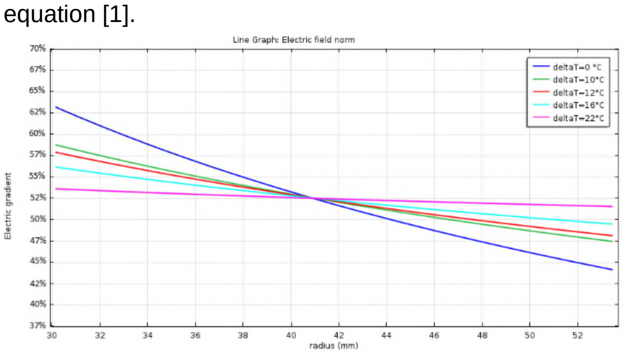

Fig. 3: Electric Field on HVDC cable insulated in HTPE

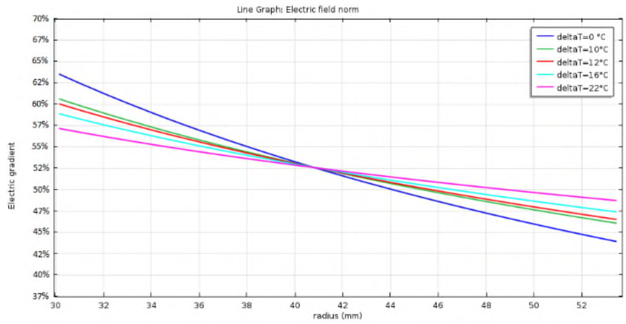

Fig. 4: Electric Field on HVDC cable insulated in XLPE

Some FEM simulations were done to evaluate the electric field on a full size HVDC 525 kV cable in different conditions of ΔT across the insulation. The temperature drop was defined as:

$$\Delta T = T_{conductor} - T_{external} \qquad [5]$$

Where $T_{external}$ is the temperature at the insulation screen.

In Fig.3 the electric field for a cable insulated in HTPE is plotted for ΔT comprised between 0°C and 22°C; with the conductivity values calculated, it's possible to see that the electric field does not inverts with ΔT up to 22 °C, the blue curve corresponds to ΔT=0°C while the magenta curve is plotted with ΔT=22°C, the electric field becomes uniform between conductor screen and insulation screen, but no inversion can be found.

The same happens with a cable insulated in XLPE, in Fig. 4 the electric fields with ΔT from 0°C to 22°C are plotted. Also in this case the field becomes more uniform between conductor screen and insulation screen with ΔT=22°C but no inversion is present.

MATERIALS FOR CABLE ACCESSERIES

When a new accessory has to be designed for a specific DC voltage level, the materials become of great importance together with the geometry of the accessory itself. The geometry is different if we talk about joints or terminations, but in general the same materials can be used for both accessories. In this case, not only the insulation plays a crucial role, in fact, for DC application it's possible to use a so called, field grading material in order to control the electric stress between the electrode and the ground.

The followings materials were assessed in order to measure the characteristic parameters:

- EPR
- Field Grading material (FGM)

The parameters to measure were:

- Breakdown strength (DC, impulse)
- Permittivity
- Electrical Conductivity

It has to be noted that also the permittivity here is of utmost importance due to two reason, the first is that the geometry of an accessory is not regular and as a consequence the electric DC field will have a different geometrical distribution respect to the impulse field.

The measurements were made on 200x200 mm plaques with a thickness of 0,5 mm, the cell used was the same as in Fig. 1.

The results were evaluated during several tests with different insulations and FGM on prototype accessories, and it was found a mismatch between the measurements on plaques and the performances of the prototypes. The parameters under suspect were DC breakdown strength, permittivity and conductivity. The reason of this mismatch probably is correlated with the nature of the materials itself; while the materials used on cable are quite homogenous, the materials used for accessories are charged with nanoparticles of different dimension and shape. This can lead to a different behavior of the material if tested with different geometries.

Another aspect to keep in account is that the accessory works not only under electrical and thermal stress, but also under constant mechanical stress. As the geometry is cylindrical, the mechanical stress is mainly radial and can have impact also on the electrical properties due to the inhomogeneity of the material.

To better assess the properties of the materials used for the accessories, hence, it was developed a different sample to use instead of the flat plaque. This new sample had the same cylindrical geometry of the final accessory, and it was possible to test it under thermal, electrical and mechanical stress (Fig. 5).

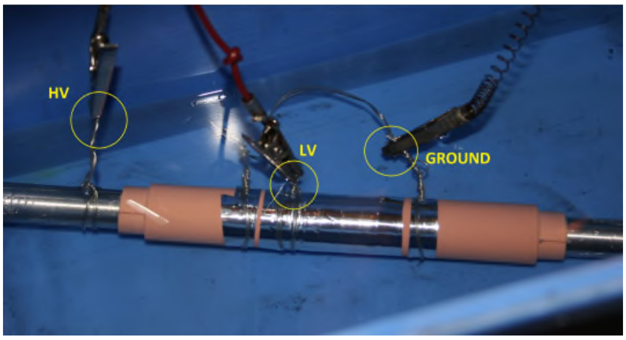

Fig. 5: Cylindrical sample

The new sample had an internal HV electrode made with a steel tube, the ground electrode was realized using aluminum tape in the central area and also the guard ring was realized with the same principle.

The measurement was performed using the same procedures as for plaques, but in addition to electric and thermal stress, the mechanical stress was also applied. This was possible using different HV internal steel tubes with different diameters and expanding the cylindrical samples into these tubes, simulating the real assembly procedure of a standard accessory.

The conductivity was measured using the circuit in Fig. 6, the HVDC is applied on the sample and the measurement is taken after 24 hours in order to have the contribution of the conduction current only.

The conduction current flows then through a shunt resistor and the small voltage drop is read by a precision voltmeter, also called electrometer.

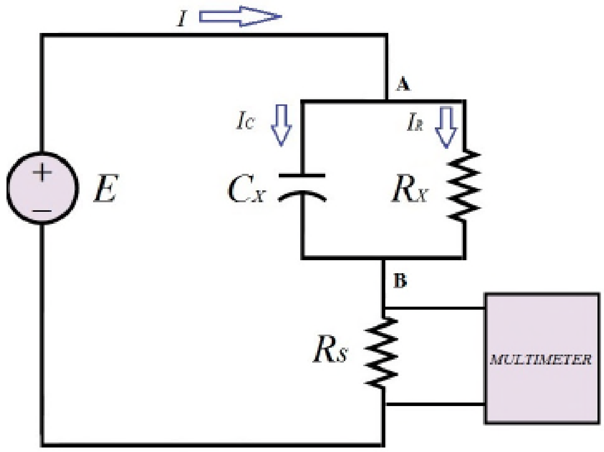

Fig. 6: Circuit used to measure conductivity

At the end of the measurements, the conductivity for each voltage level and for each temperature, for a certain mechanical stress was given by the equations [2], [3] and [4], where L is the length of the outer electrode without the guard ring.

The permittivity of the materials was measured using the circuit in Fig. 7, that is the well known Shering Bridge and allows to measure the capacitance and the dissipation factor of a sample, using a reference standard capacitor [2].

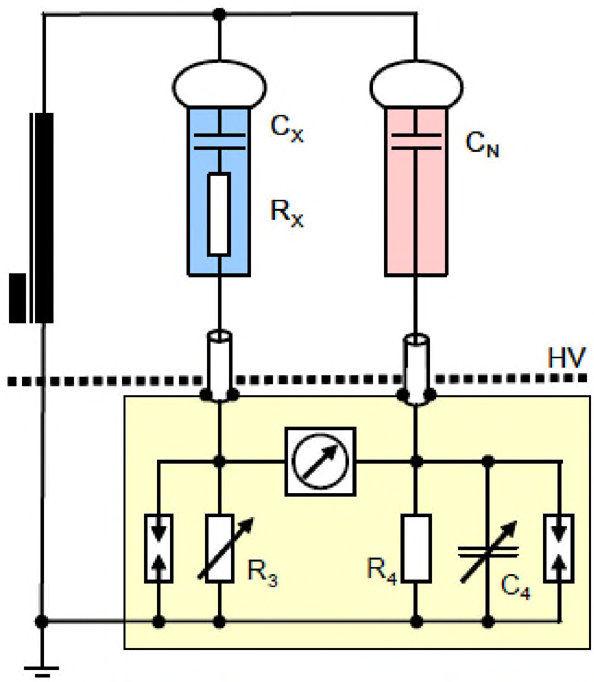

Fig. 7: Shering Bridge used to measure permittivity

For each voltage level and temperature and for each mechanical stress applied to the sample, the relative permittivity was then calculated using the relation:

$$\varepsilon_r = \frac{C_X}{2\cdot\pi\cdot L\cdot\varepsilon_o}\cdot\ln\left(\frac{Ro}{Ri}\right) \qquad [6]$$

Where Cx is the capacitance of the sample and ε_o is the permittivity of the vacuum.

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The values of permittivity and conductivity measured with the new sample gave different results respect the plaques, in some case, a material selected for the prototype accessory with the measurement on plaque, was completely rejected after the measurement on the cylindrical sample.

Furthermore, the results obtained with the new sample, were agree with the experimental data of the tests made on prototype accessories.

CONCLUSIONS

In this paper some new measurement approaches for the selection of materials for HVDC application have been described. The measurement techniques were different if the material had to be used on cables or on accessories. For cables application it was shown that with the values calculated, electric field inversion is not reached for temperature drops (ΔT) up to 22 °C and this opens further develops and R&D tests on HVDC full size cables. For accessories, it was found a mismatch between the values measured on plaque samples, and the experimental data of the tests made on prototypes. Hence, a new sample with a new geometry was developed, with the possibility to apply also a mechanical stress together with the electrical and thermal stress. The values measured on the new cylindrical sample, gave a good correspondence with the experimental data of the prototypes and some materials selected before with plaque samples, were rejected after the measurement on the new sample. This new way to measure materials for accessories will give best and reliable results and will improve the material selection for HVDC accessories application.

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