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Field distribution in HVDC Cable Accessories: Shaping Field Control Elements

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Abstract— Thermal and electrical modelling are key actions in the design of HVDC cable accessories as the experimental means for probing field distribution in such objects are still in their infancy. In this work, based on a conductivity law established from experiments on typical materials that are XLPE (crosslinked polyethylene) and EPDM (ethylene-propylene diene monomer) copolymer, we compute the field distribution in a model of 200 kV cable joint using Comsol FEM software. Alternatives in the design of stress distribution are tested for different kinds of joint materials and different thermal conditions. Although relaxation of the tangential field at hot points along the interface between cable insulation and joint insulation can be obtained, not all the process for the establishment of field distribution is mastered due to the complexity in both the object geometry and in the temperature and field dependence of the materials electrical conductivity. The paper points to the need of optimization tools to identify best conditions.

Keywords— HVDC cable accessories, finite element method (FEM), field grading, interfaces, multilayer dielectrics

I. INTRODUCTION

Accessories may represent a weak point in HVDC cable links, especially when going to ever-higher voltages where feedback on in-service behaviour is lacking. Compared to bulk cables insulation where many research works are carried out, both experimentally and in modelling for assessing insulation endurance, anticipating the field distribution in accessories is more difficult to tackle. Methods for probing charge and field distribution on localized areas are lacking, although very recently promising results with measuring space charges in cable joints were reported by the team of Prof Hozumi [1], paving the way for space charge characterization in 3D in joints under high voltage. Besides the more complex geometry, the fact that different insulating materials coexist brings further difficulty. For these reasons, thermal and electrical modelling are still necessary as a support to the design of accessories [2]. Resorting to macroscopic modelling, i.e. based on field and temperature dependencies of conductivity and/or permittivity, the numerical resolution of the problem is not a real difficulty for a given geometry and material properties set. Optimisation of the design is trickier. It must be based on reliable experimental data characterizing the materials, especially in conductivity, and also on the exploration of different practical combinations of thermal/electrical stresses that may be encountered. In

addition, the shape of the pieces constituting the joint must be wisely defined.

We previously reported on the field distribution in joints made of different kinds of joint insulation (EPDM, Silicone rubber, XLPE) with specific temperature and field dependence of the conductivity [3, 4]. By analysing simulation results in different thermal conditions (isothermal or thermal gradient), we showed that, for the particular geometry considered, the tangential field was highest when the electrical conductivity of the joint material was higher. The highest field was found near the HV deflector.

Besides material adaptation, the alternative to smooth the stress is to act on the shape of the stress elements, based on geometrical field grading. Different geometries of the deflector or stress cone are explored in order to evaluate how far the field can be redistributed, attempting to smooth field maxima near the cones. Focus is made on the tangential component of the electric field which is more difficult to tackle than the radial one, especially for understanding the respective role of geometry and thermal stress. How far the field smoothing is efficient for different materials conductivity laws is evaluated. It is recognized that the dielectric/dielectric interface represents a threat for the accessory reliability and the tangential field can be a driving mode for failure. The work points to the need of optimization tools to identify best conditions.

II. MODELLING METHOD

The field distribution was computed using Comsol Multiphysics   software, in transient conditions for both the electrical and thermal conditions. Details of the constitutive equations are provided in [4]. Fig. 1 shows a representation of the modelled joint with variants in the geometry. The outer surface of the joint is set at the ground potential. Herein, we provide results for the field distribution along the z axis, at the interface between XLPE and the joint insulation material. Three geometries are considered: the reference one (A) used in previous work; a second one where the shape of the central deflector has been smoothed by setting the radius of the lower part to 6 mm instead of 2 mm (B). The last configuration is that with a redrawn stress cone using a larger radius (C).

A thermal gradient can be generated by injecting a current in the conductor. The stress conditions consisted in applying a DC voltage of +200 kV for 24 h, followed by grounding for

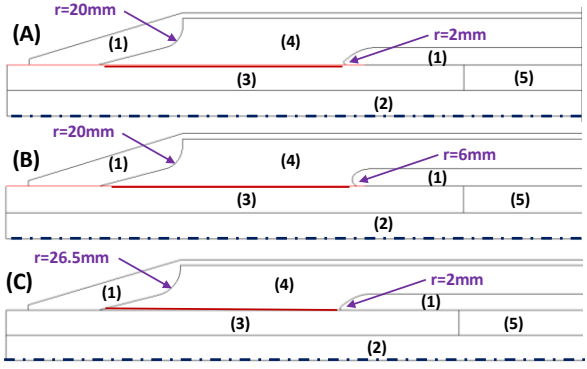


Fig. 1. The different joint geometries investigated. (A) reference geometry (B): modified deflector; (C) modified stress cone. The red line outlines the interface between joint insulation (4) and XLPE (3). (1): semicon; (2): cable conductor and soldering; (5): heat distributor.

3 min, and application of -200 kV for 24 h. The initial thermal condition is an isotherm of 30°C. Except otherwise stated, a current of 1 kA is injected in the conductor when the voltage is applied, producing a slow heating of the joint. The investigated temperature range is 30-80 °C and the obtained fields in the joint are in the range 0-10 kV/mm.

The expressions and parameters taken for the conductivity are available in [4], and the conductivity dependence in temperature and field for each material is presented in Fig. 2. EPDM has a higher electrical conductivity than XLPE at low field / low temperature and the order is inverted at high temperature / high field. SiR has a higher conductivity than XLPE, practically field-independent and weakly temperature-dependent. Hence, not only the temperature gradient but also the absolute temperature is influential in the field distribution.

The thermal conductivity is 0.38, 0.30 and 0.20 W/m/K for XLPE, EPDM and SiR respectively, producing an enhanced temperature in the joint in the case of SiR compared to XLPE. The temperatures at the interface between XLPE and the joint insulation, after 24 h, are of about 55, 57 and 64 °C for XLPE, EPDM and SiR, respectively [4]. The conductor temperature reaches 70°C in case of XLPE/EPDM joint.

III. RESULTS

A. XLPE/EPDM joint with smoothed deflector

Mainly results obtained on the tangential field distribution are shown as it is the most critical parameter for reliability [5, 6]. Besides, the behaviour of the radial component of the field is rather straightforward to understand. Fig. 3 shows the field

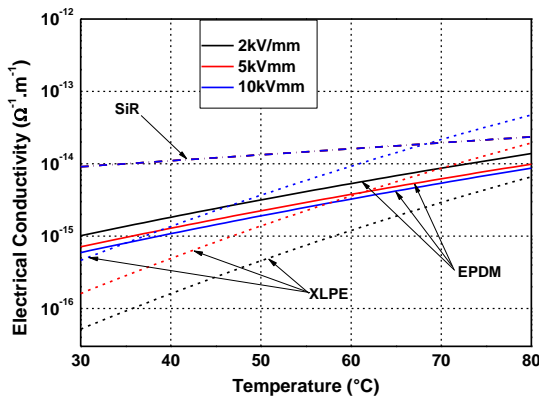


Fig. 2. Temperature dependence of the electrical conductivity of XLPE (---), EPDM (—) and SiR (-----) at different fields.

distribution at different times under stress for the reference geometry A. The field evolves as a function of time due to a shift from a capacitive distribution to a resistive one with a variation also influenced by the increase in temperature due to Joule effect in the conductor. After 24 h, it is considered that a steady state is reached both thermally and electrically. The field is increasing with time under the stress cone while decreasing near the deflector. The field evolution during the transient stage is well represented by the distribution at grounding (bold curve). This residual field adds to the capacitive field just after stress polarity reversal to -200 kV.

With the smoothed deflector, Fig. 3b, the field is significantly reduced near the deflector. Already the maximum capacitive field is reduced from 7.3 to 4.0 kV/mm. The maximum steady state field is also reduced. Even after polarity reversal the field stays under 5 kV/mm. On the cone side, there is no noticeable difference between the two cases.

B. Joint with smoothed deflector: comparison for different materials

Fig. 4 compares the field profiles obtained just after voltage application, at the end of the 24 h polarization time and after grounding for geometries A and B and for the three joint materials. Such profiles are representative, respectively, of the impact of the geometry on the capacitive field distribution, the resistive distribution, and of the residual field resulting from the mismatch of capacitive and resistive field distributions.

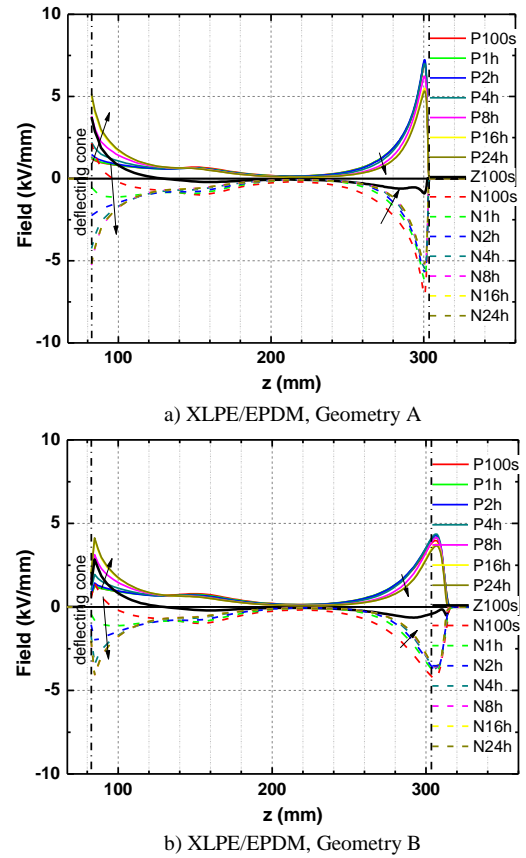


Fig. 3. Axial field distribution at the XLPE/EPDM interface (red line in Fig. 1) at different times after voltage application, for geometries (A) and (B). The temperature is initially 30°C and a current of 1 kA is injected in the conductor at the time of voltage application. Vertical lines define insulator boundaries. The curves in black correspond to voltage set to 0V after 24 h at +200 kV. Ground on the left; HV on the right.

Considering the field profiles obtained just after voltage application (100 s), it can be observed that the differences obtained for the different geometries are the largest for the SiR joint material and the lowest for the XLPE. As the modifications of the geometry were achieved at the level of the central deflector, what is observed under the stress cone is a transfer of the potential, i.e. essentially a proportional variation (increase) of the tangential field. The larger field decrease observed for SiR has to be related to the relative permittivity differences between the materials, that were taken as 3.5, 2.9 and 2.3, respectively for SiR, EPDM and XLPE. The increase in permittivity of the joint material leads in principle to a move of the capacitive field into the insulation of the cable (XLPE). Then, as the stress is moved away from the geometrical cone, the tangential contribution is reduced. This explains the decrease in the tangential field value when changing the joint material from XLPE to EPDM and to SiR.

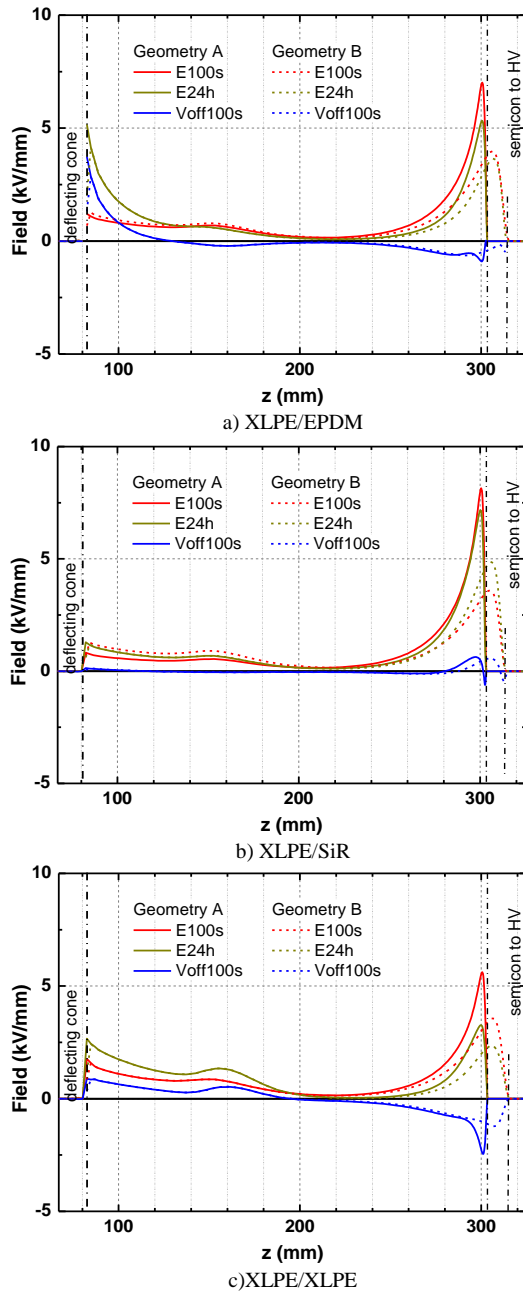


Fig. 4. Tangential field distribution at different times, for different joint material, for geometries (A) and (B), and for the stress conditions given for Fig. 2.

However, on the deflector side, because of the sharp geometry A, a high divergence of the field is produced, resulting in the highest tangential field for Fig. 3b. When improving the geometry, the highest field reduction is obtained in this case of high ϵ (56%), see Table I.

According to Table I and Fig. 4, the reduction in maximum field is less in the resistive case (24 h) than in the capacitive case (100 s). The reason could be that the non-linear character of the conductivity already induces a smoothing of the resistive field distribution. Explaining features in terms of relative value of conductivity of joint material and XLPE is not easy, as it changes depending on temperature and local field modulus, see Fig. 2. For SiR, which has a relatively simple conductivity law, for a temperature of 64°C, and field modulus of about 10 kV/mm, the conductivities of XLPE and EPDM are about the same, while their permittivity ratio is 1.5. This may explain why the maximum tangential field at long time is greater than that at short time for geometry B.

TABLE I. MAXIMUM FIELD (kV/MM) NEAR THE DEFLECTOR AS A FUNCTION OF TIME, GEOMETRY AND JOINT INSULATION MATERIAL, NON-ISOTHERMAL CASE.

Material	EPDM		SiR		XLPE	
Design	A	B	A	B	A	B
$E_{\max}(100 \text{ s})$	7.02	3.97	8.14	3.59	5.60	3.56
Reduction %		44		56		37
$E_{\max}(24 \text{ h})$	5.33	3.05	7.14	4.87	3.27	2.35
Reduction %		43		32		29

C. Dependence on joint temperature

As the temperature has a very strong effect on the relative values of conductivity, it is expected that the geometrical field grading depends on joint temperature. Fig. 5 shows the field profiles for EPDM joint material in isotherm condition at 30°C, to be compared with Fig. 4a for the same arrangement under thermal gradient. The resistive field distribution produces a substantial increase of the maximum field, reaching 9.62 kV/mm after 24 h. With the modified deflector the field decreases to 6.34 kV/mm, i.e. by 35%, which represents less improvement than under thermal gradient. The high steady state field near the deflector is presumably due to the higher conductivity in the EPDM compared to XLPE: the field is displaced into the XLPE under the cone, the tangential field is less, and the potential is reported on the deflector.

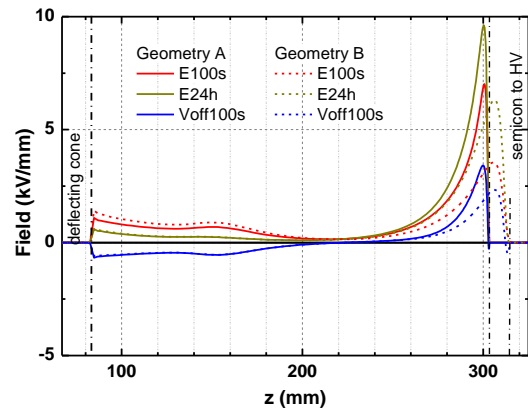


Fig. 5. Tangential field distribution at 30°C for EPDM as joint material. Electrical stress as previously, with no heating.

IV. DISCUSSION

According to the obtained results, smoothing the deflector edge represents an improvement in the maximal tangential field near the deflector without bringing major drawback in the field distribution, all considered including transient under polarity reversal (this can be appreciated considering the residual field in volt-off). Fig. 6 shows a map of the field distribution in the case of EPDM joint material, split into its radial and axial components, and comparing geometries A and B at 100 s and 24 h of polarization, representing the capacitive and resistive field distributions, respectively. The field appears more homogeneous around the deflector in case of geometry B. This goes with a strengthening of the field in all the cone region (probably because of voltage redistribution), particularly for the results at 24 h. One can notice that in situations of relatively high permittivity or conductivity mismatch, the smoothing of the field is not so efficient with the explored configurations (cf. cases of Fig. 4b and Fig. 5). Computations have been achieved with modifying the shape of the cone according to Fig. 1. An example of result for the tangential field distribution is shown in Fig. 7 for EPDM under thermal gradient, one of the worst cases regarding field distribution under the cone (cf. Fig. 3a). Differences in the capacitive field distribution are visible, but not in the resistive one. It must be admitted that the changes produced are not significant, one of the reason being that the modifications are too far from the interface. Changes in the angle of the cone and more important inflexion of the shape should be more effective in modifying the field along the interface region.

The obtained results show that it is quite difficult to invent a configuration producing a reasonably homogeneous distribution of the field in all the transient phases of electrical and thermal stresses. It is indeed not easy to clarify the way the stress in the material redistributes as the thermal and electrical stresses are not homogenous and the materials have complex responses. The use of field grading layer at the interface between cable and joint insulation is one solution [7], which however may bring issues in definition, realization and reliability. A necessary step for refining the design is with using optimization tools. The capacitive field distribution is relatively easy to master as the permittivity of materials is relatively invariant. Minimizing AC stress remains an entry to

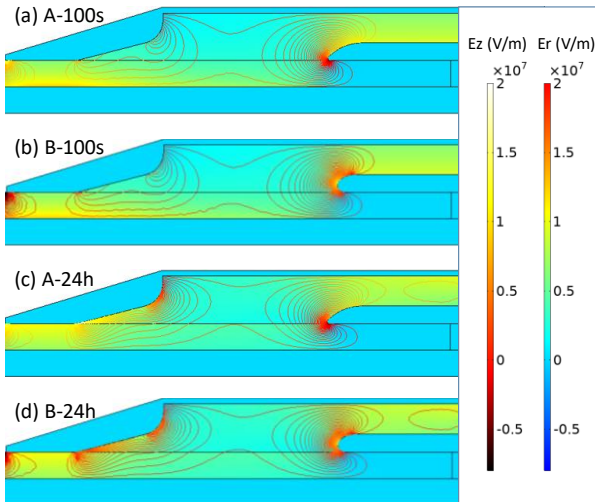


Fig. 6. Distribution of the axial field (E_z , contour lines) and radial field (E_r , maps) for (a, c) geometry A; (b, d) geometry B, 100s (a, b) and 24h (c, d) after voltage application.

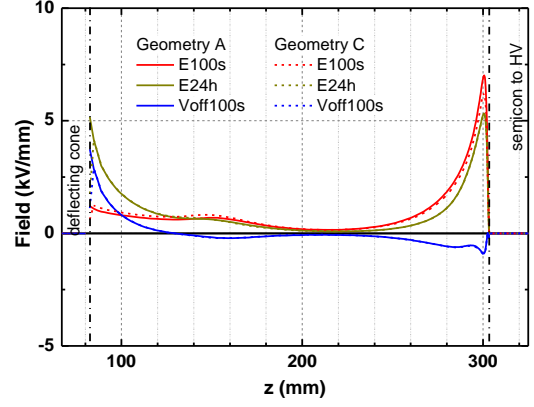


Fig. 7. Tangential field distribution for EPDM joint material comparing geometries A and C (modified cone). Same thermal and electrical conditions as for Fig.3.

DC accessories design as anyway the transient steps and surge voltages must be supported. The geometrical design of the joint, and the specification of the material for joint insulation could be refined using optimization methods. This also goes with the definition of criteria to minimize the stress.

V. CONCLUSION

The challenge in managing the stress distribution in HVDC cable accessories was presented. The geometry of stress grading elements, the complex field and temperature dependence of the electrical conductivity, the thermal gradients make the field distribution difficult to anticipate and variable with time and temperature. A smoothing of the field maxima can be obtained by smoothing the shape of the stress grading elements. However, a global improvement of the design would necessitate to implement optimization methods.

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