Technical challenges linked to HVDC cable development

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Abstract

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Results. Figure 3. An example of leakage current curve measured on an insulation plaque sample under DC voltage.

b) Modeling and design

There are two different materials, one needs to pay careful attention to the differences between the plaques and the cables to avoid wrong conclusions from plaque sample than plaques so the same material can behave differently in plaque and cable. The electrode material also may be different in plaque studies than cables. On insulation are inherently ignored in plaque sample studies. Besides, the cables undergo a different production process (i.e. temperature, time and atmosphere) plaque samples studies. Cables have much thicker insulation than the typical plaque samples, therefore the effects related to the volume and thickness of need to be compared and the best alternatives would be candidates for model cables or experimental cables. There are challenges in the interpretation of measurements. The same is valid for other DC measurements such as space charge measurements. Starting from plaque samples studies, different materials development, to modeling, design, production, quality control to testing, there are many challenges which need to be overcome in order to assure the quality of the final product.

a) Material development

What are the properties of an ideal extruded HVDC insulation material? Beside the properties of a good HVAC electrical insulation such as high electrical withstand, chemical stability and good aging properties the DC conduction behavior of the material also needs to be considered. Conductivity and space charge behavior have been the focus of study on many different insulation materials. But even simple properties such as conductivity can be challenging to measure. Figure 3 shows an example of typical leakage current curve from a plaque sample measurement. The leakage current continues decreasing even after a rather long period of time. This makes it hard to assign a stable conductivity value to a material based on such measurements. The same is valid for other DC measurements such as space charge measurements. Starting from plaque samples studies, different materials need to be compared and the best alternatives would be candidates for model cables or experimental cables. There are challenges in the interpretation of plaque samples studies. Cables have much thicker insulation than the typical plaque samples, therefore the effects related to the volume and thickness of insulation are inherently ignored in plaque sample studies. Besides, the cables undergo a different production process (i.e. temperature, time and atmosphere) than plaques so the same material can behave differently in plaque and cable. The electrode material also may be different in plaque studies than cables. On top of all the differences mentioned above, in cables, temperature gradient through the insulation has an effect on the conduction phenomena in HVDC cables. This effect can be challenging to be simulated by plaque samples. Although plaque samples are very convenient and simple way of comparing different materials, one needs to pay careful attention to the differences between the plaques and the cables to avoid wrong conclusions from plaque sample results. Figure 3. An example of leakage current curve measured on an insulation plaque sample under DC voltage.

b) Modeling and design

There are two
main approaches to conduction modeling of HVDC insulation materials. In the charge carrier transport model [5] [6], a number of charge carriers (mainly electron and hole) are considered being transported through the insulation. A charge carrier with a density of \( n(k)n \) leads to a partial current density \( j(k)n \). The diffusion constant \( D(n,k) \) and the drift speed \( v(n,k) \) will govern the movement of each charge carrier. 

\[ j(n,k) = D(n,k) \left( \nabla \frac{1}{n} \right) + v(n,k) \left( \frac{1}{n} \right) \]

The total apparent current density is the sum of all partial current densities from different charge carriers plus the polarization current: \( j \). In addition to the equations above, one needs to define boundary conditions for each charge carrier. The boundary conditions depend on electric field, temperature, and the chemical composition of the insulation/electrode interface. To be more accurate one needs to rethink the polarization equations and take into account the temperature and polarization time constants as well. Obviously, such an approach to modeling leads to a complicated model with large numbers of constants which the result can be sensitive to the defined constants. Therefore, good knowledge of all charge carriers is needed to reach reasonable results. On the other end of spectrum, being pragmatic, one can assign a conductivity function to the material which is a function of electric field, temperature [7] and chemical composition or location: \( E[\text{ET}] \). Together with other self-explanatory equations: \( VE[\text{E}] \) and the generic conduction model for solid HVDC insulation material [8], the space charge \( \varepsilon \) can be written as:

\[ \varepsilon(n,k,t) = \frac{\partial q}{\partial t} + \nabla \cdot J(n,k) \]

The model is then complete with simple heat transfer equation: heatpm STk t T c [11]. The electric losses due to conduction are provided from the electric field and conductivity as: \( 2 \varepsilon \text{Heat} \) [12]. The task left is then to find the functionality of conductivity on temperature, electric field and location in the insulation. This is usually done by conductivity measurements on plaques, or cables together with space charge measurements. Different proposed models can be found in literature [8]. Using this model, one has to remember the simplifications involved in the formulation of the model, being the assumption that an inherent property of the insulation material as conductivity can indeed be defined, and it can be defined as a function of field, temperature and location. The advantage of this model is that it is rather robust and converges to reasonable results, but as it should be expected it does not explain all of observed phenomena. 

**c) Production and quality**

In order to achieve higher voltages, it is not feasible to simply scale the insulation thickness. Instead higher voltages have been introduced by increasing the insulation thickness and average electric field at the same time. This is possible by developing new insulation materials and production techniques and increasing the quality of the produced cables. In HVDC cables, besides the typical HV cable quality control techniques, such as PD measurement, AC voltage withstand and in-line geometrical measurements, new techniques need to be applied. Since the DC conductivity of insulation materials can vary by the amount of unwanted chemicals, new requirements on the so-called "Chemical Cleanliness" apply. To do so, the effect of different chemicals on the conduction in the insulation material needs to be understood and controlled. In case of nano-composites, the concentration and distribution of the particles will be added to the quality control list. Therefore new methods for quality assurance and quality control of the cables with filled insulation need to be developed.

**FUNDAMENTALS OF MI CABLES**

What happens inside a MI cable? The insulation system of a MI cable is built up of many thin layers of high density paper impregnated with a high viscous insulating compound concealed in a metal sheath. This insulation type has been used for over a hundred years, first starting with MVAC cables and since the 1950s in HVDC cables. The insulation system is in a different state when the cable is loaded compared to when the conductor carries no current. In the former case the conductor and the compound are expanded due to their positive temperature expansion coefficient. The compound is also in a low viscous state. The insulation underneath the metal sheath is now well-filled. When the current is switched off, the conductor and compound cool down. This results in contraction of these components; the pressure close to the conductor falls. While the compound tries to flow back to the regions of low pressure (close to the conductor) this becomes more difficult as viscosity increases. In the end some regions will not be completely back-filled and due to the under-pressure voids may arise. These voids will typically be present in the butt-gaps. In this unloaded cold state, the MI cable is in its weakest state, contrary to the extruded cable. Although this sounds dangerous this does not need to be the case as the compound is to a certain extent self-healing. Small carbon traces in the compound can be "washed" away. Partial discharges, \( n \) and \( q \) When voids and an electric field are present in the insulation, partial discharges may occur. A classic way to start a description of partial discharges is using the abc REE N°4/2014 VI Technical challenges linked to HVDC cable development scheme [12]. With the aid of this scheme the repetition rate \( n \) can be derived. It is given by:

\[ n = \frac{r m r s r r E K E n}{1 \text{ min}^{1/4}} \text{ h} \]

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where \( r, m, r, s, r, E, K, E, n \) and \( 1 \text{ min}^{1/4} \) which stands for the time constant of the void, Emin for the minimum breakdown field of the void, Es for the asymptotic field of the void, E for the actual electric field in the void, relates the residual field Eres in the void to Emin by:

\[ E_{\text{res}} = \frac{E_{\text{min}}}{1 - 1/4} \]

The advantage of this model is that it is rather robust and converges to reasonable results, but as it should be expected it does not explain all of observed phenomena. 

**Production and quality**

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