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Technical challenges linked to HVDC cable development

Marc **JEROENSE**, Markus **SALTZER**, Hossein **GHORBANI** ABB AB, (Sweden),
marc.jeroense@se.abb.com, markus.saltzer@se.abb.com, hossein.ghorbani@se.abb.com

ABSTRACT

HVDC as a large scale concept has been in commercial use since the 50's. Nowadays paper cables impregnated with a high viscous compound (mass impregnated – MI), oil pressurized cables and HVDC extruded cables coexist. The paper will concentrate on MI and extruded cables, and their principal strong and weak points. For MI cables the fundamental link between the pressure dynamics, cavity volume and partial discharges is highlighted, while for the polymer insulation system, the importance of conductivity as one of the basic properties is stressed. In the paper also some principles of field control in accessories of extruded cable systems are summarized. Challenges towards development of these systems as well as the testing situation are mentioned.

KEYWORDS

HVDC Cable Systems; HVDC Cables; XLPE Cables; Mass Impregnated Cables; MI-cables; HVDC Cable Accessories

INTRODUCTION

There is a world-wide increased demand for electrical energy. Consequently, generation, transmission, and distribution capabilities and concepts must be increased and be made more efficient. The two basic alternatives are alternating current (AC) and direct current (DC) transmission systems. Due to losses DC is nowadays in many cases the preferred technology for large powers and long distances. On land, power can be transmitted by overhead lines or underground cables, while for sub-sea transmission only cables are available. Current commercial voltage levels are e.g. 800 kV for overhead line systems [1], whereby 1100 kV are discussed [2], and 500 kV for land and sea cable systems [3].

Politically, there is an underlying driving force, which is the European climate and energy 20/20/20 targets, defined by the European Commission [4], requiring an adaption of current network structures. As a result, the vision of a pan-European energy market is exemplified in the generation of the Ten-Year Network Development Plan as drafted by ENTSO-E. A strong growth in the number of wind energy projects in the North Sea of Germany is seen, and on the midterm the number of wind energy projects around the UK and along the French and Spanish coasts is also expected to increase. Additionally, initiatives on the interconnection of the energy networks of countries and continents around the Mediterranean, e.g. DESERTEC, Transgreen and Dii, have been started. Overall a strong demand on sub-sea, long distance, high power transmission is expected, leading to increased activities in HVDC cable system development.

Mainly two cable technologies are commercially available for HVDC at the moment: mass impregnated (MI) cables with a combination of kraft paper and oil based compound as insulation system and extruded cables with cross linked polyethylene (XLPE) as insulation material. As depicted in Figure 1. The MI-cable is a lapped technology, where the kraft paper is lapped around the conductor including semiconducting and insulation layers and afterwards impregnated as a whole cable in an impregnation vessel. For XLPE the polymeric layers, i.e. the semiconducting layers and the insulation layer, are extruded in one extrusion step.

Figure 1. Cable models of a MI-cable (left) and an XLPE cable (right).

In the following some challenges with respect to the demand of increased power transmission and higher voltages in HVDC cable systems will be described. The main focus is hereby on extruded XLPE cables, MI cables, as well as stress grading in extruded cable systems.

FUNDAMENTALS OF EXTRUDED CABLES

A typical extruded HVDC land cable structure is shown in Figure 2. An aluminum or copper conductor is covered with a thin semiconducting layer to have a smooth interface to the following insulation layer. A second semiconducting layer covers the insulation. Usually these three layers are extruded in the same step. Depending on the application and design other layers are added to the cable. For example, in case of damage to the cable, swelling tape absorbs water and expands, blocking the water from moving axially along the cable. The screen wires are grounded. Aluminum laminate provides a diffusion barrier against foreign substances, especially humidity. And finally the covering sheath jackets all layers. Beside the mentioned layers, sea cables usually include an extruded lead sheath as water barrier and armoring wires provide mechanical protection to the cable and take the burden of the cable weight during installation.

As for electrical insulation of HVDC cables different options exist. Since its introduction, HVDC grade XLPE has been the main material used for insulation of HVDC cables. Currently the highest operation voltage for HVDC XLPE cables is 200 kV and cables up to 320 kV are produced and being installed. Thermoplastics such as polyethylene and polypropylene and filled concepts with XLPE or thermoplastics are other alternatives for extruded HVDC cable insulation.

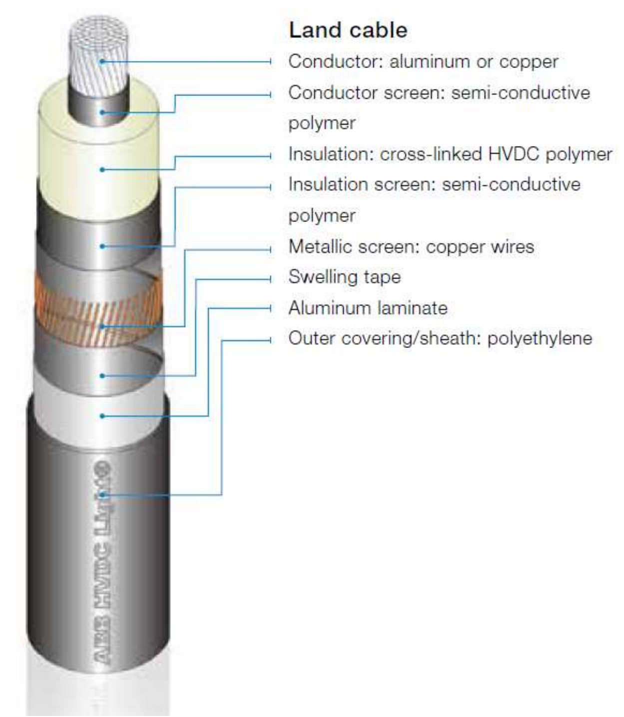

Figure 2. Typical HVDC land cable.

From insulation material 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.

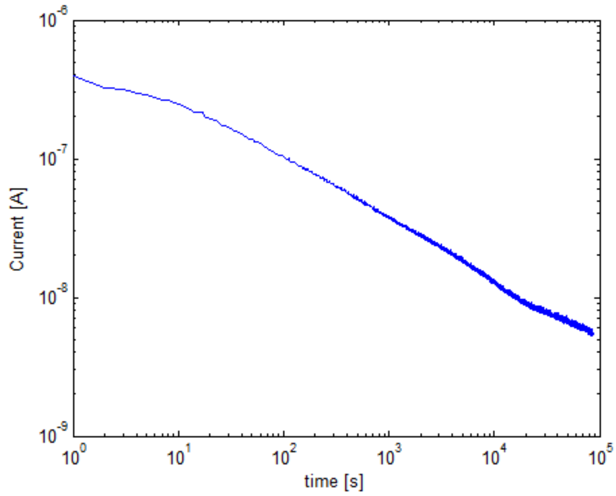

Figure 3. An example of leakage current curve measured on an insulation plaque sample under DC voltage

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) leads to a partial current density j_k:

$$\frac{\partial n_k}{\partial t} + \frac{\partial j_k}{\partial x} = R_k(n_l) \quad [1]$$

$R_k(n_l)$ represents phenomena such as recombination, ionization, etc. The drift diffusion equation will then govern the movement of each charge carrier:

$$j_k = n_k \upsilon_k - D_k \frac{\partial n_k}{\partial x} \quad [2]$$

where D_k is the diffusion constant of the carrier and the

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drift speed is a function of electric field and carrier mobility:

$$\upsilon_k = \mu_k E \qquad [3]$$

The total apparent current density is the sum of all partial current densities from different charge carriers plus the polarization current:

$$j = \sum_k q_k j_k + \frac{\partial D}{\partial t} \qquad [4]$$

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 number 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:

$$\sigma = f_R(\vec{r}) f_T(T) f_E(E) \qquad [5]$$

Together with other self-explanatory equations:

$$E = -\nabla V \qquad [6]$$

$$\rho_e = \nabla \cdot (\varepsilon_0 \varepsilon_r E) \qquad [7]$$

$$\nabla \cdot j = -\frac{\partial \rho_e}{\partial t} \qquad [8]$$

$$j = \sigma E \qquad [9]$$

the space charge ρ_e can be written as:

$$\rho_e = -\frac{\varepsilon_0 \varepsilon_r}{\sigma} \frac{\partial \rho_e}{\partial t} + j \cdot \nabla \left(\frac{\varepsilon_0 \varepsilon_r}{\sigma} \right) \qquad [10]$$

The model is then complete with simple heat transfer equation:

$$\rho_m c_p \frac{\partial T}{\partial t} = \nabla \cdot (k \nabla T) + S_{heat} \qquad [11]$$

The electric losses due to conduction are provided from the electric field and conductivity as:

$$S_{heat} = \sigma |E|^2 \qquad [12]$$

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 scheme [12]. With the aid of this scheme the repetition rate n can be derived. It is given by

$$n_r = \frac{1}{\tau_r}\frac{E_{s,r}}{E_{\min,r}(1-\alpha_r)} = K_1\frac{1}{\tau_r}\frac{E_r}{E_{\min,r}(1-\alpha_r)} \quad [13]$$

in which τ stands for the time constant of the void, E_{min} for the minimum breakdown field of the void, E_s for the asymptotic field of the void, E for the actual electric field in the void, α relates the residual field E_{res} in the void to E_{min} by $\alpha U_{min}=U_{res}$, the suffix r relates all the quantities to the location with radius r and K_1 relates the asymptotic field to the field in the void by $E_s=K_1E$. Typical values of K_1 are estimated between 1 and 5.

The magnitude q of a single discharge when approximated to a flat void is given by

$$q = \varepsilon_0\varepsilon_r\frac{A}{h}U_{\min}(1-\alpha) = \varepsilon_0\varepsilon_r AE_{\min}(1-\alpha) \quad [14]$$

where A is the surface area of the void, the voltage U is related to the field strength E by $E_{min}=U_{min}/h$ and h stands for the height of the void. For a circular void we can state that $A=1/4\pi h^2$. And when we introduce the radial dependence the equation becomes the following

$$q_r = \tfrac{1}{4}\pi\varepsilon_0\varepsilon_r h_r^2 E_{\min,r}(1-\alpha_r). \quad [15]$$

One should remember that this charge magnitude q is the displacement of charge *at the site* of the discharge, not the *measured* one. Measuring the discharges is based on the measurement of the charge displacement in the leads to the cable. One can calculate the measured charge $q_{M,r}$ by using the following equation

$$q_{M,r} = q_r\frac{C_{b,r}}{C_{b,r}+C_{c,r}} \approx q_r\frac{C_{b,r}}{C_{c,r}} \quad [16]$$

in which C_c is the capacitance of the void and C_b is the capacitance of the healthy insulation in series with the void (see he Figure) and $C_{b,r} << C_{c,r}$.

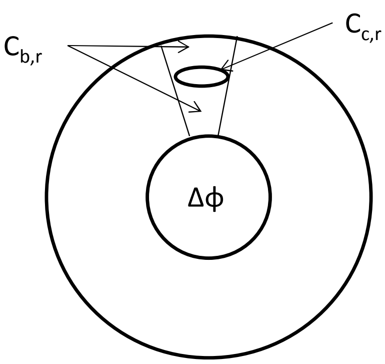

Figure 4. The capacitances C_b and C_c in a cable.

The location dependent capacitances are given by

$$C_{c,r} = \frac{2\pi\varepsilon_0\varepsilon_r}{\ln\left(1+\frac{h_r}{r}\right)}\Delta\phi$$
$$C_{b,r} \approx C_b = \frac{2\pi\varepsilon_0\varepsilon_r}{\ln\left(1+\frac{t}{R_i}\right)}\Delta\phi \quad [17]$$

in which t denotes the insulation thickness and R_i the inner radius of the insulation. Now $q_{M,r}$ can be written as

$$q_{M,r} = q_r\frac{\ln\left(1+\frac{h_r}{r}\right)}{\ln\left(1+\frac{t}{R_i}\right)} \approx q_r\frac{\frac{h_r}{r}}{\ln\left(1+\frac{t}{R_i}\right)} \quad [18]$$

by having recognized that $h_r/r<<1$ and having used the Taylor expansion of the logarithm. If then expression [15] is used one finally arrives at

$$q_{M,r} = \tfrac{1}{4}\pi\varepsilon_0\varepsilon_r h_r^3 E_{\min,r}(1-\alpha_r)\frac{1}{r\ln\left(1+\frac{t}{R_i}\right)} \quad [19]$$

The product n times q

When carefully looking upon the expressions for the local repetition rate n_r and the measured local discharge magnitude $q_{M,r}$ one can see that they contain a number of unknowns that are difficult to get certain knowledge of, like α and E_{min}. An easy way out, is to multiply the two quantities. The resulting product nq has even a very interesting physical meaning, which is elaborated below. Multiplying equations [13] and [19] gives

$$nq_{M,r}(=n_r q_{M,r}) = \frac{\frac{1}{4}\pi K_1\varepsilon_0\varepsilon_r}{\ln\left(1+\frac{t}{R_r}\right)}\frac{h_r^3}{\tau_r}\frac{E_r}{r} \quad [20]$$

The time constant describing the recharging process is governed by the surrounding insulation as well as by the discharge by-products that are created on the walls of the void that even may change with time. Making an approximation and stating that the time constant is that of the surrounding insulation only, namely $\tau=\varepsilon_0\varepsilon_r/\sigma_r$, with σ_r being the local conductivity of the insulation. Then the product can be written as

$$nq_{M,r} = K_2 h_r^3\sigma_r\frac{E_r}{r}$$
$$K_2 = \frac{\frac{1}{4}\pi K_1}{\ln\left(1+\frac{t}{R_i}\right)} \quad [21]$$

The number of voids per unit length of cable at radius r is named D_r. The product nq_M can then be calculated per unit length of cable the contributions of all the voids are added,

$$nq_M = K_2\sum_r h_r^3 D_r\sigma_r\frac{E_r}{r}. \quad [22]$$

Now a simple expression for the product nq_M has been derived, as it can be measured (magnitude q_M and the repetition rate n independently). It relates to two electrical quantities, the electric field E and the conductivity σ and to

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two physical parameters, like the void distribution *D* and the void height *h*. In the following it is elaborated a bit what this really means.

Physical meaning of the product *nq*

Taking a continuous view and replacing the sum with an integral gives,

$$nq_M = K_2 \int\limits_{insulation} h_r^3 \Theta_r \sigma_r \frac{E_r}{r} dA \qquad [23]$$

In this integral representation, Θ_r represents the number of discharging voids per unit volume at location *r*, $D_r=\Theta_r dA$. The infinitesimal surface *dA* stands for a slice of insulation as depicted in Figure 5. Therefore equation [11] can be written as follows,

$$nq_M = 2\pi K_2 \int\limits_{insulation} h_r^3 \Theta_r \sigma_r E_r dr \qquad [24]$$

The integral describes a coupling between a purely electrical quantity, namely the electrical current density $j_r=\sigma_r E_r$ and a purely void-dynamic quantity, the *cavity volume* per unit volume of cable insulation $v_r=4/3\pi h_r^3\Theta_r$. We may therefor write,

$$nq_M = \tfrac{3}{2} K_2 \int\limits_{insulation} v_r j_r dr \qquad [25]$$

This equation is not easily calculated as there exists no closed expression for neither the cavity volume nor the current density at every point in time. However, one can approximate, by recognizing that

$$\frac{\partial v_r}{\partial r} >> \frac{\partial j_r}{\partial r}, \qquad [26]$$

stating that the cavity volume changes much faster as a function of location than the current density. This has been verified by computer simulations using a very extensive cable model, of which the explanation goes far beyond the intention of this paper. If j_r is replaced by a location independent mean value denoted by

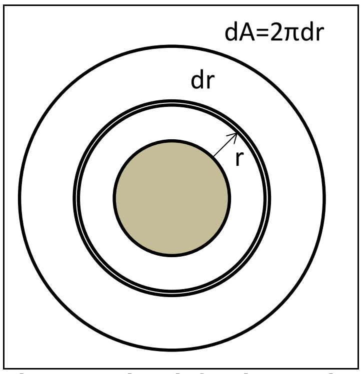

Figure 5. Sketch for the continuous view on *nq*

$$\bar{j} = \frac{I_M}{2\pi R_m} \qquad R_m = \frac{R_o - R_i}{2} \qquad [27]$$

where we fixed the current density at the value in the middle of the insulation in between the inner radius and the outer radius and where I_M denotes the measured leakage current through the entire insulation. Then expression [25] changes into

$$nq_m = \tfrac{3}{2} K_2 \bar{j} \int\limits_{insulation} v_r dr = K_3 I_M V \qquad K_3 = \frac{3K_1}{8t \ln\left(1+\frac{t}{R_i}\right)} \qquad [28]$$

where it has been used that $\int v_r dr$ equals the total void volume *V*, the cavity volume, per unit length of cable. Rewriting a last time ([28]),

$$V = \frac{1}{K_3}\frac{nq_M}{I_M} \qquad [29]$$

One can see that, indirectly, the cavity volume of a MI cable can be derived by measuring two simple pd quantities and the leakage current.

When having performed heavy mathematical exercises and detours along the horizon of approximation it sometimes is good to make a reflection whether the result makes sense. So it does! Partial discharge activities (*nq*) are of a high frequency character and occur only in the voids of a MI cable, not in the well-filled areas. The slow leakage current flows in the rest of the insulation. Please also recognize that the product *nq* can be seen as a kind of current (charge per unit time). So, the quotient of a high frequency component of the current only acting in the voids and the low frequency component taking place in the rest of the insulation is indeed related to the cavity volume.

Clearly, the challenge of developing next generation MI cables is in controlling the processes as described above. If one introduces new designs, processes or materials the void dynamics has to be understood.

FIELD CONTROL IN EXTRUDED CABLE SYSTEMS

A further challenge related to HVDC cables concerns less what happens in the bulk cable, but rather, what happens at the cable end, i.e. where a cable has to be terminated, or two cables have to be jointed. In order to end a cable the HV conductor has to be connected, e.g. either to a HV bus bar or to another cable conductor. Then, the grounded layer of the cable either has to be terminated or connected to the ground layer of another cable. In the case of the termination of the ground layer, a termination is the proper device to apply to the cable end, while for

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connecting two cables/ground layers a joint is the proper cable accessory to use. In both cases the field control of the terminated ground layer presents a challenging problem. The electric field in this region is strongly non-uniform, and especially in HV an unacceptable high field enhancement occurs. The weak spot is then usually the interface from the cable to the accessory close to the ground layer termination.

From alternate current (AC) cable systems, various field grading (FG) technologies are known to improve the field distribution, e.g. [9]. A common approach for field control is for example the use of additional electrodes or other conductive parts, like e.g. metallic corona rings, or specifically applied to the ground layer termination of a cable, a deflector shield made of conductive rubber, as depicted in Figure 6. For electric field applications where no significant charging of the dielectric takes place, e.g. AC, surge and pulse fields, the shape of such "capacitive" or "geometrical" field control devices can usually be calculated, [9]. The underlying properties are the tangential electric field as a weak point in the system, and the relative permittivity of the involved insulation materials. In Figure 6 this is the cable insulation material and the joint insulation filling the gap between the cable and the deflector.

Figure 6. Sketch of deflector shields, grey material layers, made out of conductive rubber in a HV cable joint. The joint insulation material is sketched in blue, the cable insulation in white, and the cable ground layer in black color.

If the field distribution is dominated by charging of the system through conduction currents as in the resistive state of a HVDC system, the conductivities of the involved materials are the relevant characteristics. While the permittivity of different materials typically only varies within a decade, the conductivity generally varies even within one material by several decades, e.g. depending on temperature or electric field as mentioned above in equation [5]. Consequently, for DC the field distribution may drastically change given different thermal and field conditions.

Such an effect is illustrated in Figure 7. The equipotential lines under applied DC voltage of a geometrically graded cable end are shown in dependence of the temperature of the cable conductor. The latter is modeled with different load scenarios. Equations [5] – [12] can be used with proper material parameters to model such a scenario. The region with the main voltage drop, i.e. the region with enhanced electric field is indicated by a dashed box, and I will strongly change in dependence of the load scenario. As a consequence a geometric grading in a HVDC system has to be laid out to the worst case of all possible occurring wave shapes, which could be DC, surge or pulse fields, or polarity reversal scenarios. Good knowledge of the material properties in dependence of a wide range of parameters is inevitable, for a design, and

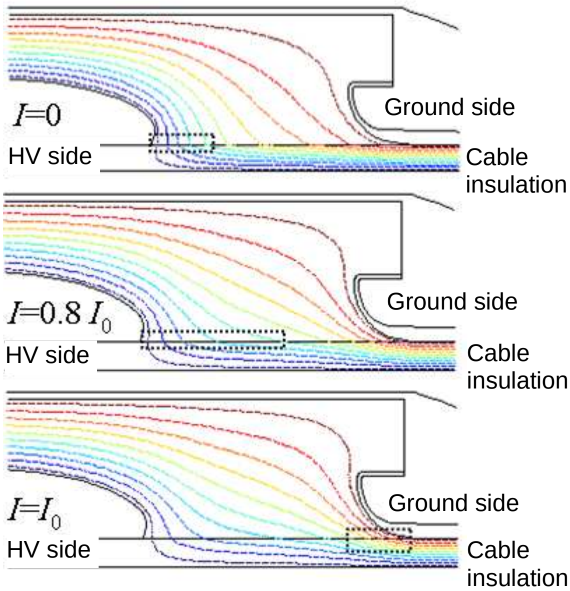

Figure 7. DC equipotential-lines for the geometric graded cable end for three different current-load cases, i.e. thermal scenarios in the conductor. The dashed box shows the region for 50% voltage drop along the cable-joint interface

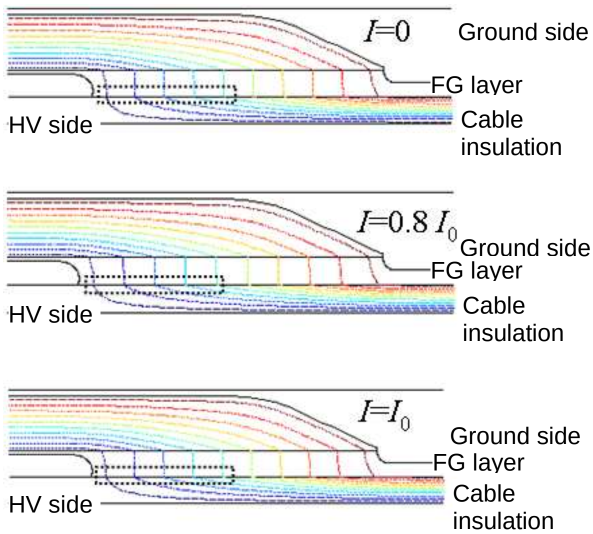

Figure 8. DC equipotential-lines for the non-linear resistive graded cable end for three different current-load cases, i.e. thermal scenarios in the conductor. The dashed box shows the region for 50% voltage drop along the cable-joint interface

even then a robust static design is challenging for a highly dynamic DC system.

A possible alternative FG solution, with dynamic self-adjustment of the stress control properties, might be provided by non-linear FG materials, specifically in the case of DC non-linear resistive FG materials (FGM). The latter materials change reversibly their electrical state from being insulating to conductive, in regions, where the field exceeds a (critical) value E_b, A typical functional form to approximate this behavior might be

$$f_E(E) = \left(\frac{E}{E_b}\right)^{\alpha} \quad [30]$$

or superposition thereof, and typical values are E_b = 0.1 – 10 kV/mm, and α = 1.5 – 20. In this FG solution a non-linear FG material layer covers the ground termination of the cable and the remaining end section towards the HV electrode, including the latter electrically. This is sketched in Figure 8, where simulated equipotential lines under applied DC voltage for a non-linear resistive graded cable end are shown in dependence of the temperature of the cable conductor. It can be observed, that the region with the main voltage drop, indicated by a dashed box, is spread out, i.e. there is almost no region with with enhanced electric field. Moreover this situation is stable for different conductor temperature scenarios. Therefore such a FG solution would represent a rather robust electric field distribution.

The characteristic σ(*E*) of a non-linear resistive FG material may be tuned according to regions that are determined by the electric design fields *E*, required for the expected stresses in the cable system, e.g. nominal stress, surge, pulse conditions, on one hand , and leakage current as well as heating conditions, on the other hand [10], see Figure 9.

In a simple picture the FGM becomes active after a time

$$\tau_e = \frac{\varepsilon_0 \varepsilon_r}{\sigma} \quad [31]$$

note that σ is field dependent, which has to be compared to the time of the applied voltage stress (τ_S and τ_P for surge and pulse, respectively). Backwards, from the stress-time requirements a suitable conductivity can be derived. Today's FGM technology is based on SiC and, in particular, ZnO microvaristor filled polymers, but also alternatives are coming up. The FGM characteristics can be fine-tuned by appropriate choice of the process parameters, cf. e.g. [11]. However, know-how in the area of FGM is a prerequisite for the proper design and development of FGM for HVDC and still represents a big challenge in itself.

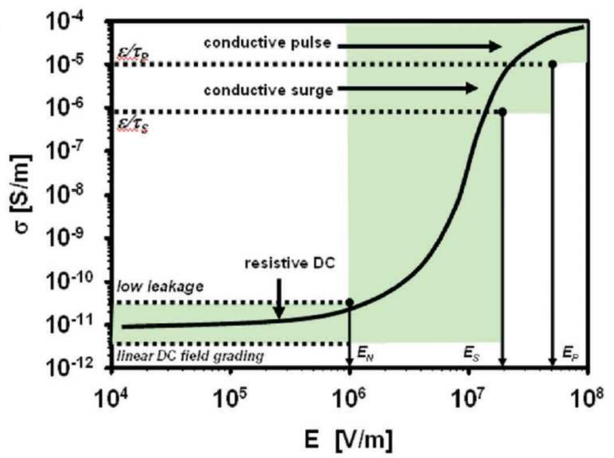

Figure 9. Qualitative illustration sketch of how regions are determined in the E-σ plane for the σ(E) curve of an ideal nonlinear-resistive field grading material in dc applications taken from [10].

CABLE SYSTEM TESTING

Testing of cable system is being done in different regimes. CIGRE brochures, recommendations and publications do not tend to divide the different test into the following categories, development tests, type tests and long term tests, routine tests, factory acceptance tests and after laying tests. We here disregard from what is called sample tests and special tests. All of these categories have their own purposes. It is important to use them in the correct way in in their right context.

Development tests are the arena where the scientists and engineers develop new products, new theories and new ideas. A wide range of measurement principles is available and may be used. Standards and recommendations give large freedom in this category and do not demand sequences of certain tests.

Long term tests and type tests are two types of qualifying tests. Type tests have the purpose of qualifying the object(s) under test for the intended application. Whereas long term tests are to be performed in order to demonstrate satisfactory long term performance of a cable system and shall be carried out only once. Whereas type tests qualify the technical solution, long term tests qualify the technology. These tests are performed on shorter pieces of cables (tens to hundred meter) and few accessories.

Routine tests and factory acceptance tests are made on every single meter of cable and every accessory to check that the component meets the specified requirements. The same is true for a factory acceptance test that is being done on the final delivery object. It has often also a legal character as it might be the point in time where the object is taken over by the customer or an installing company.

The after laying test is then made on the installed cable system to demonstrate the integrity of the cable system as installed.

The two different cable types as treated in this article are governed by different testing documents. The MI cable is tested according to another CIGRE Recommendation as the extruded DC cables are, electrically. The mechanical testing – qualification – is performed using the same recommendation for both cable types.

For future development of cable systems it is important that the test recommendations and standards are being looked over and revised if necessary. Future cable systems will operate at higher voltages. Test factors for heat cycling are defined as 1.8 for DC MI cables and 1.85 for extruded DC cables. It must be avoided to choose test voltages levels such that they will ignite processes that will never occur during the life time of the cable system at operating voltage. In other words, the dielectric mechanism shall if possible not arrive in another regime during qualifying tests as compared to during operating under service voltage. Future cables with higher voltages will probably operate at higher electric field stresses. This means probably that the margin to a new dielectric regime will shrink. This in turn means that it should be debated in future whether the test factor shall be adopted, that is, lowered. Maybe, if thought to be necessary, while introducing other environmental stresses aspects or tests that compensate for such a decrease.

Yet another aspect that will influence routine testing and factory acceptance testing is the future increase in both voltage and length. Extruded DC cables are sometimes routine and factor acceptance tested with an AC voltage. AC voltage is seen as a good means to detect defects in polymer cables. Even if it can be debated, that nor the AC stress distribution neither the aging process under AC is similar as that under DC stress. But letting these arguments pass by, we will face an increase of testing power needed. As future delivery lengths and service voltages increase (and AC routine test voltages are related to those), the routine testing equipment is increasing in complexity and value.

The current in a cable during testing at a voltage U_T is given by

$$I = 2\pi f C U_T \, . \qquad [32]$$

Recognizing that the capacitance *C* can be written as the capacitance per meter of cable *c* times the length *L* of the cable under test, this becomes

$$I = 2\pi f c L U_T \, . \qquad [33]$$

The power *P* in MVA that the equipment must deliver to the cable under test is equal to $FU_T I$ which is then given by

$$P = 2\pi f c L U_T^2 \qquad [34]$$

where it can be seen that the power increases with length and test voltage. But it also decreases with decreasing test frequency. A 100 km 500 kV DC cable routine tested at, say 300 kVAC, with a per meter capacitance of 300 pF/m needs testing power of roughly 1 GVA, which is really a lot ! Going down to a test frequency of 0.1 Hz would end up with a 500 times less power, that is, 2 MVA.

CONCLUSION

The demand for increased energy transmission and distribution capabilities includes also a demand for HVDC cable systems with higher voltages motivated by lower losses and drives the development of cables and its accessories suitable for higher voltages.

The relevant physics for MI and extruded cables is quite different. In MI cables, the fluid dynamics and the formation of voids in the insulation during cooling is the main phenomenon which needs to be controlled. The fluid dynamics coupled with electrical conduction govern the PD which is the limiting factor in MI cables.

In extruded cables on the other hand, physics behind conduction, relevant lab scale measurements, interpretation of measurements, understanding of conduction and finally relevant and reliable quality assurance techniques are the main areas of improvement.

In extruded cable accessories, the main objective has been and will be the control of electric field at the interface between cable and accessories. This has to be done properly for DC and transients, such as superimposed impulses. This demands good knowledge of the DC and dynamic properties of the insulation materials involved as well as their interaction. Non-linear FGM combined with good geometrical design represents a good option for compact and robust field control, but also requires a good knowledge and experience.

To finalize, there are still many challenges in the scientific world of cable power transmission in order to fulfil the future demands of global energy generation and distribution.

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