

Materials for HVDC cables

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ABSTRACT

The market for HVDC cables has grown substantially lately, e.g. due to the offshore wind farms. Extruded HVDC cables are qualified up to 320 kV but the wish for increased power transmission is a drive to go beyond this level. This paper discusses the requirements for insulation material. First with regard to more general materials properties, e.g. thermo-mechanics and processability. The electrical properties, DC conductivity, space charges and breakdown strength, are of course essential. For all three the cleanliness, both physical and chemical is important. The emphasis of the paper deals with the need to decrease electrical conductivity.

KEYWORDS

HVDC cables; XLPE; space charges; electrical conductivity.

BACKGROUND

The demand for HVDC (high voltage direct current) cables has grown substantially the last 10 years. One driver is the switch in energy generation towards more renewable resources such as wind power, another being the integration of the network with both land and submarine links, e.g. in Europe. Compared to HVAC cables transmission of power over very long distances is much more attractive using HVDC cables. Buried cable links are also favourable with respect to the project permission process due to the invisibility and the reduction of magnetic and electrical fields.

The first operational commercial HVDC cable was installed 1954 between the island of Gotland and mainland Sweden and was operating at 100 kV and 20 MW [1]. This was a mass-impregnated cable consisting of insulating paper impregnated with high viscosity oil. The voltage and power rating of this type of cables have continued to increase and is now reaching 600 kV DC. The operational performance has so far been found to be very good.

On the other hand, extruded cables with crosslinked LDPE (XLPE) offers many benefits, both from cable production cost and an environmental point of view. The first commercial DC cable with XLPE insulation was installed on Gotland in Sweden, operating at 80 kV in a VSC (voltage source converter) system [1]. As no polarity reversals are needed in VSC systems eventual problems with decreased insulation performance due to accumulated space charges are reduced. The combination of XLPE HVDC cables and the VSC technology has increased the HVDC power transmission applications, e.g. for offshore wind farms. The operational experience of extruded HVDC cables is excellent and the total installed length is in similar order as that of paper impregnated cables [2]. Currently HVDC extruded cables

based on XLPE insulation is offered up to 320 kV and around 1000 MW. Several 320 kV systems are under construction in Germany, France and Sweden and will be operational 2014-15.

Converter technology is already available for voltages well above 320 kV and there is a clear market need for cable systems with increased power transmission capacity. Several concepts to develop XLPE materials to meet the electrical requirements necessary for HVDC cables operating above 320 kV have been presented [2 – 4]. This paper discuss the properties of both filled and unfilled XLPE materials, both with respect to a more general material perspective and to the most essential electrical properties, e.g. electrical conductivity, breakdown strength and space charge behaviour.

GENERAL MATERIALS PROPERTIES

Apart from the electrical characteristics, which of course are essential, there are several requirements that the materials intended for use as in an extruded HVDC cable must fulfil, both with respect to the production of the cable and its use. For a cable operating well above 320 kV you would expect an insulation thickness of 20 – 30 mm and in order to keep stiffness low enough the modulus of the insulation material should be rather low. The typical modulus of LDPE meets this requirement quite well. The thermal properties of LDPE are however limited considering the temperature of the conductor under load, temperatures in the range 60 – 90 °C are mentioned in the recommendations from Cigré [5]. In order to meet the demands for mechanical integrity at these temperatures the material is crosslinked. This produces an excellent material with high stress cracking resistance and very good heat deformation properties.

Also the rheology properties of the insulation material are important when producing a HVDC cable. At one hand you want a low viscosity at the extrusion condition to have a high output from the extruder. On the other hand, the thick insulation layer and the need to heat up the material to induce the crosslinking, in combination with the requirements on a symmetric end-product, call for a high zero rate shear viscosity. LDPE with its pronounced shear thinning properties is a good choice also to meet these requirements.

Altogether these properties contributed to the high impact of XLPE for AC cables developed during the last 50 years. They are also important when extruded HVDC cables are developed and make XLPE to the first hand choice in this application.

The crosslinking is initiated by a peroxide, usually dicumyl peroxide (DCP), which leads to several decomposition products, e.g. methane, acetophenone and cumyl alcohol remaining in the insulation layer. The two latter have a

negative impact on the DC electrical properties (see below), while methane creates fire hazards during installation of the cable. For these reasons it is common practice to degas the cables to decrease the concentration of these substances. The DCP level, and thus also the amount of generated decomposition products, can be lowered by using Borealis Borlink™ Supercure technology, including a LDPE with increased reactivity for crosslinking due to an increased content of vinyl groups introduced by using a diene as comonomer. In this way less peroxide can be used to reach a given level of crosslinking. This is illustrated in Figure 1 which shows the amount of DCP needed to reach 100 % hot set for an ordinary LDPE and a LDPE with about 5 times more vinyl groups. [6].

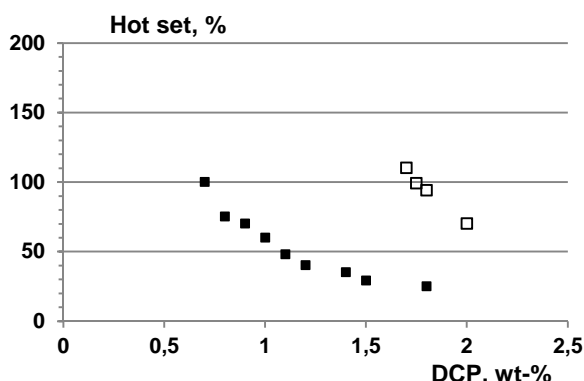


Fig. 1. Hot set determined at 200 °C of XLPE as a function of DCP content; □ ordinary LDPE; ■ LDPE with increased vinyl content. Adopted from ref.6.

ELECTRICAL PROPERTIES

With respect to the electrical properties of the insulation, conductivity, space charges, and DC and impulse break down strength are the most important for a HVDC cable. The break down strength is to a large extent influenced by the physical cleanliness of the material, i.e. the presence of foreign particles. This is illustrated in Figure 2 which shows the effect of different contaminants (50 – 60 µm) on the Weibull breakdown parameters of LDPE discs tested under DC [7]. It is obvious that contaminants can have a strong effect on the breakdown strength depending on the nature of the contaminant. Amber with its low conductivity had a limited effect while air led to a drastic decrease in breakdown strength.

Space charges are accumulations of localised electric charges (electrons, ions) inside the insulation. This can e.g. be caused by uneven distribution of polar components like peroxide decomposition products, or by the presence of "traps"; localised chemical or physical entities that could trap charge carriers. An example of the effect of peroxide decomposition products on the total stored amount of space charges is given in Figure 3.

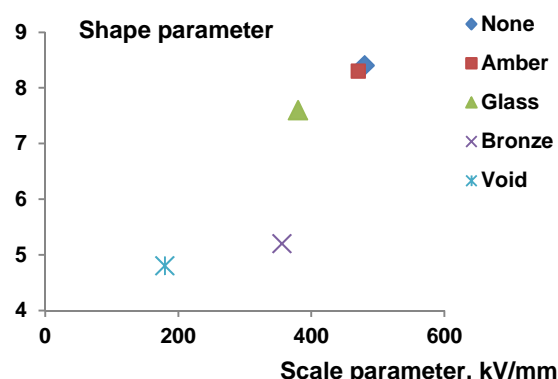


Fig. 2. The effect of added contaminants (50 – 60 µm) on the Weibull breakdown parameters of LDPE discs tested under DC. Adopted from ref. 7.

The problem with space charges is that they will change the electric field distribution with time and in an unpredictable way. Very high stress might arise especially at polarity reversal. One way to approach this problem has been to use nanosized particles, in particular MgO [8, 9] although other materials have been investigated as well, see e.g. [10]. In their development of a HVDC material J-Power Systems from Japan have used nanosized particles and showed that they indeed have a significant effect on space charges when compared to an unfilled AC XLPE [3]. The field enhancement factor (FEF) for the DC material stayed below 1.1 independent on temperature and time. The AC material on the other hand showed FEF values above 1.2 and, most important, increasing with electrical field strength and time.

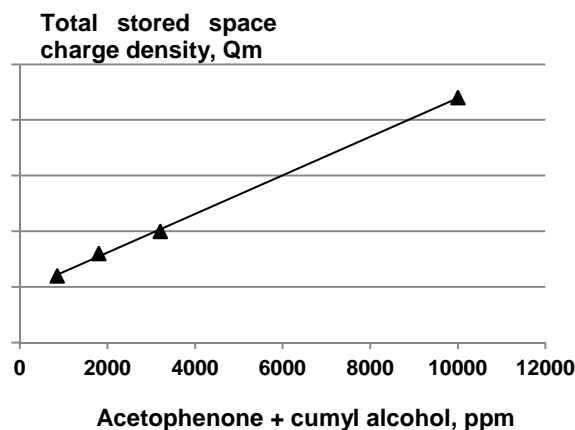


Fig. 3. Total stored space charge density as a function of the total amount of DCP decomposition products.

It has been pointed out however that dispersion is important when nanofillers are used [11]. If the dispersion is not complete larger aggregates may be present and this can lead to decreased breakdown strength [11] in line with the effect of foreign particles mentioned above. This effect will increase with increased loading and in many papers the optimal loading of nanofillers are often said to be 5% or lower. It is possible to improve dispersion by a proper surface treatment of the filler. The degree of dispersion will however also depend on the specific processing

conditions and there is thus a risk that this concept not will provide a robust solution.

During the last years there has been increased emphasis to reduce the conductivity of the material [12]. The driving force for this has been that the leakage current through the insulation may lead to a temperature increase. The temperature under load is essentially controlled by the temperature of the conductor which is given by the electrical current. Depending on the loading conditions this will give a certain increased temperature level of the insulation. The leakage current can then cause an additional temperature increase. As the conductivity increases with the electrical field this effect is expected to be more important when the voltage is increased beyond 320 kV. In addition, the conductivity will also increase with the temperature, i.e. with increased temperature the leakage current will increase even more leading to further temperature increase and thus increased conductivity. If there is no balance between heat generation and cooling this may lead to thermal runaway and cable breakdown. For HVDC cables heat generation due to the leakage current is in fact a mechanism that limits the electric field applied to the insulation.

As the heat generation depends on the conductivity \times (electrical field)² the conductivity must be decreased significantly to reach voltages well above 320 kV. The conductivity in an insulation material depends on the presence of polar molecules assisting in the charge transport process. The conductivity σ can be expressed as the sum of the contribution from each kind of these molecules:

$$\sigma = \sum_i n_i \cdot q_i \cdot \mu_i$$

where; n_i = concentration of charge carrier, q_i = charge of charge carrier, and μ_i = mobility of charge carrier.

The most obvious way to decrease the conductivity is thus to decrease the concentration of potential charge carriers or polar substances assisting charge transport, i.e. to increase the chemical cleanliness of the material. Although LDPE generally is assumed to be a very clean material as there is no catalyst residues there are of course polar molecules in the finished cable insulation, e.g. process chemicals from the polymerization, peroxide decomposition products, antioxidants and other additives.

It is equally important to consider the mobility of the charge carrier. This is coupled to diffusion rate of the substance in question. It is e.g. well known that low molecular weight polar compounds like the peroxide decomposition products leads to increased conductivity, see below. On the other hand a low level of polar units on the polymer, e.g. introduced by oxidation, does not increase the conductivity; on the contrary even decreased conductivity has been observed for low levels of oxidation [13]. At higher levels of oxidation the conductivity increases as expected.

The mobility can also be affected by changing the properties of the polymer. It is e.g. well known that the higher crystallinity in HDPE leads to much lower permeation rates of diffusants and it would thus also lead to decreased DC conductivity. Another way to decrease the mobility of charge carriers is to introduce a strong adsorbent to trap the carriers. The reduced conductivity

reported [3] for nanofillers is most likely due to this effect.

Looking at the approaches presented in the literature two different ways have been used to obtain low conductivity of the insulation material. In one approach an additive is used to mitigate the problem [3, 4], e.g. by decreasing the mobility of the charge carrier with a trap like MgO. In the other approach [2] the conductivity of the XLPE compound is minimized without using a trap. In such a development of HVDC insulation materials the equation above can be used as a toolbox to decrease the conductivity. This can be applied to the full production cycle, e.g.:

- The effect of process chemicals on the conductivity of the base resin
- Reduced amount of peroxide decomposition products
- A careful selection and optimization of all additives

As an example Figure 4 shows the effect of peroxide decomposition products on the conductivity. Increased degassing or reduced initial amount of peroxide will thus contribute. The increased reactivity of the BorlinkTM Supercure materials from Borealis offers a way to decrease the amount of peroxide needed, see above.

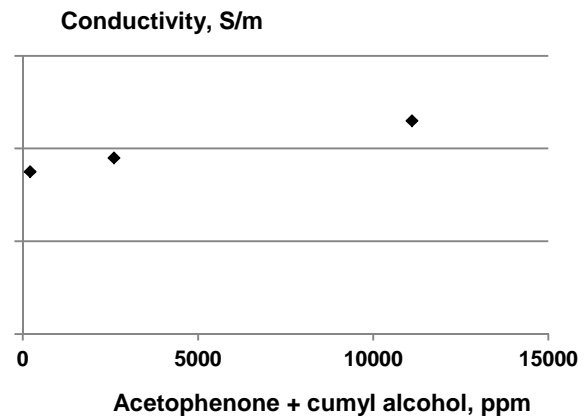


Fig. 4. The DC conductivity as a function of the total amount of DCP decomposition products.

There are thus several possibilities to reduce the DC electrical conductivity. What could then be necessary to prevent thermal runaway? The temperature rise in the insulation due to leakage current, ΔT , can be written [12] as:

$$\Delta T = \sigma \cdot E^2 \cdot \left(\frac{d^2}{2k} + \frac{d}{h} \right)$$

where E = the electrical field, d = insulation thickness, k = heat conductivity of insulation, and h = heat transfer coefficient. With typical values of d , 15 -30 mm, and of the two constants k and h [12] it turns out that the $d^2/2k$ term is roughly 10% of the d/h term and the parenthesis is therefore mainly proportional to d . Using $E = U/d$, where U

is the applied voltage, and considering that the insulation thickness is not varied over a large range, the equation above can therefore be approximated with: with:

$$\Delta T_{rel} \propto \sigma \cdot U^2$$

In Figure 5 this equation has been used to plot three lines for the **relative** temperature rise, one for the present HVDC material intended for 320 kV and two for materials having 50 % and 10 % of the conductivity of the present material, respectively. Note that only relative conductivities are used. Therefore the ΔT values are relative and no values have been given for the y-axis.

For increased voltages thicker insulations are used and then the approximation with a constant d leads to a too high value. It must further be stressed that the conductivity has been assumed to be constant for each line. This is not correct as the conductivity increases with both temperature and the electrical field strength. In the reference case the effect of temperature is most likely quite large and thermal runaway is expected to happen as indicated by the dotted line. For the 10% case the temperature effect can be neglected but instead the electrical field will be important. The field will of course increase with the voltage but at certain levels this will be counteracted by increased insulation thickness. The dashed line represents a principal scenario for this case.

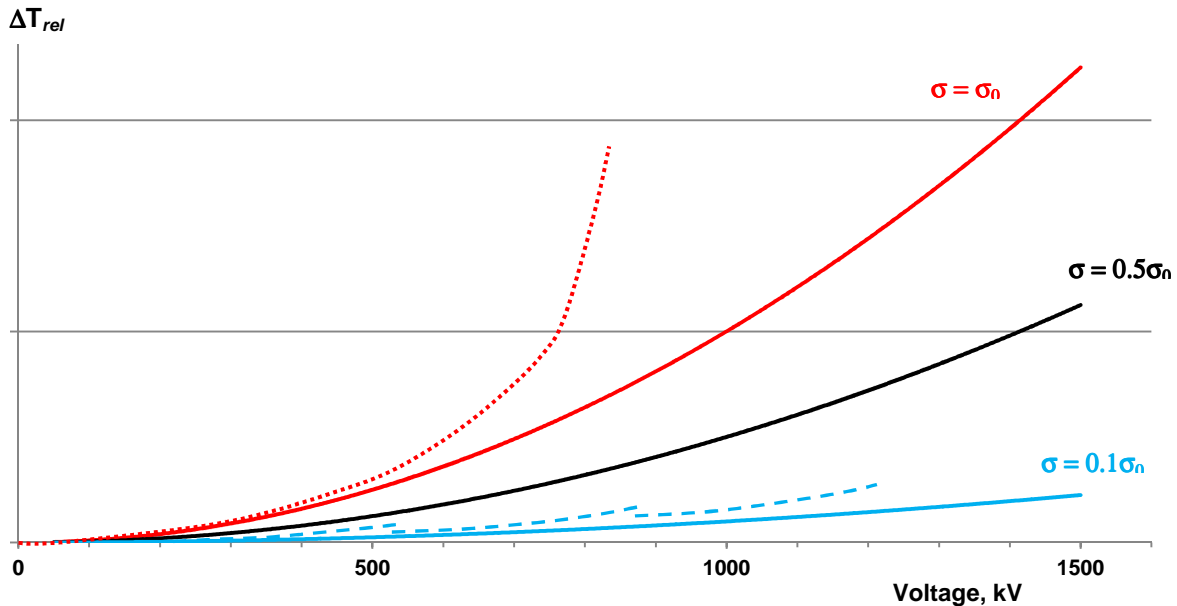


Fig. 5. The effect of the voltage on the relative temperature rise for three levels of conductivity. For approximations and explanation of the dotted and dashed lines see text.

Present commercial materials are qualified up to the 320 kV level according to the tests recommended by Cigré. If conductivity of the insulation material and the resulting temperature rise due to the leakage current is the limiting factor it is obvious that a decrease of at least one order of magnitude in conductivity is needed in order to reach a HVDC cable that could work well beyond the present level. It is of course important that the low electrical conductivity is maintained during the full production cycle, i.e. from base resin, over compound to finished cable. It is further important that other properties meet the requirements as well. This includes e.g. thermo-mechanical properties, processability, ageing performance and other electrical properties like space charges and breakdown strength.

CONCLUSIONS

There are many properties that materials intended for use in extruded HVDC cable must fulfil. The development of XLPE for HVDC has now led to materials meeting the requirements for 320 kV. The electrical properties, conductivity, space charges and breakdown strength, are of course the most critical. To be able to meet the increased demands in cables intended for higher voltages both physical and chemical cleanliness is of outmost importance. A clear conclusion is that the temperature rise due to leakage current in the insulation is a very critical aspect. For that reason the DC conductivity must be decreased significantly compared to that of the present commercial materials.

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