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The development route towards extra high voltage DC – materials and testing

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ABSTRACT

A novel XLPE material has been developed to meet market demand of increased transmission capacities. The property profile focussing on balance between electrical, mechanical and crosslinking was demonstrated with ultimate verification resulting in successful type and pre-qualification testing at the record level of 640 kV according to Cigré TB496. The development route and methodology used have been described. The key design requirement identified was low DC conductivity which was reached through a very high chemical and physical cleanliness.

KEYWORDS

HVDC, insulation, conductivity, materials

INTRODUCTION

The increasing demand for power generation from renewable energy resources such as wind and solar and the need to balance and trade between different energy markets have during the last decade started to transform the landscape of the electrical grid. This will in Europe according to the TYNDP (Ten Year Network Development Plan) issued by ENTSOE (European Network of Transmission System Operators for Electricity) continue to reshape the electrical grid in the forthcoming years [1]. The supply and demand balancing also becomes increasingly important with the fluctuations arising from the non-linear electricity generation of the renewable power sources becoming more dominant in the grid together with economic considerations. Cables have become a complement to overhead lines especially for water crossings, areas of natural beauty and densly populated regions. The long distance transmissions are not possible with AC (Alternate Current) cables due to its losses over longer distances needing power compensation; hence DC (Direct Current) cables have increasingly become the alternative transmission technology to support needed grid investments. So far two main technologies of HVDC cables have been employed: lapped paper technology and extruded polymeric insulation based on crosslinked low density polyethylene (XLPE). The lapped paper technology was introduced for DC in the 1950's and is even used today, especially in installations for the highest voltages at 500 kV and above. However, during the last decades the development and use of XLPE has increased rapidly and presently operating at the 320 kV level. The market demand for higher transmission capacities has continuously pushed the development of extruded cable technology towards higher voltage levels which previously only were reachable using lapped paper technology. Within the crosslinked polyethylene technology two routes for development have been identified when reviewing the literature: either by utilisation of the high cleanliness potential of polyethylene composition or by addition of nano-fillers [2]. The first route is the leading technology used in almost all the commissioned DC transmissions links in operation today. This paper will discuss the further development of this technology for EHVDC (Extra High Voltage Direct Current) proven by successful pre-qualification and type test at 640 kV level according to the recommendations of Cigré TB496. The material technology fundament builds on superior cleanliness both in term of physical and chemical contaminants resulting in a material designed to have a balanced electrical and mechanical property profile in order to fulfil the high demands of this application. In addition to enabling the use of renewable and sustainable energy sources in an efficient way this material can be recycled into other applications when reached end of life as a HVDC cable [3].

BACKGROUND TO DESIGN PARAMETERS FOR EHVDC DEVELOPMENT AND TESTING

The material that should be able to operate at the EHVDC level and the testing thereof has to be carefully engineered in order to fulfil the tough property requirements. It is not only enough to take care of the electrical design parameters but also (long term) mechanical performance needs to be consistent over the life of the cable.

Electrical performance

Having mentioned the need to increase transmission capacity of a cable link, there are in principle two ways possible to achieve this: either increase the voltage or increase the current. The latter is in general less favourable as an increase in current would inevitably lead to higher ohmic losses in the conductor and heating. Increasing the voltage is however not straight forward either as there are several aspects to take into account such as DC conductivity, electrical ageing, and phenomena related to space charges. In this development the challenge to increase the voltage was chosen as the route to increase transmission capacity.

Up until recent years the focus of the research community for development of DC materials has been on reducing and controlling the space charge profile of the insulation systems. The focus on space charges comes from the fact that the early DC converters only could switch power flow direction by changing the polarity of the cables. This was seen to have implications if the materials contained a significant amount of space charges as it can have detrimental effect on the insulation material and in worst case lead to an electrical breakdown. The development of DC converter technology with the introduction of the VSC

(Voltage Source Converter) made it possible to change the direction of power flow without changing the polarity. This reduces the importance of the space charge build up, however as described in macroscopic models the space charge is the gradient of DC conductivity which in term is governing the electrical field in general, a low and controlled amount of space charges is still desirable. However, successful type testing of XLPE material according to Cigré TB496 for conventional HVDC converters with polarity reversal has also been reported [4].
In this work the well known PEA (Pulsed Electro Acoustic) technique was used to determine the space charge properties using semiconductive sheets as the electrodes. The PEA test was used to determine the influence of long term thermo-oxidative ageing at elevated temperature on the space charge properties. Cable core samples with 10 mm insulation thickness (described in more detail later) were aged at 135°C and after different ageing times a thin sample, 0.15 mm, was lathed from the middle part of the insulation layer and the space charge characteristics were determined at 70°C and 30 kV/mm.

DC conductivity was early on identified as the key parameter to decrease and control in order to take the insulation system to the next level in terms of voltage rating [5-7]. This was the corner stone for the development of this next generation DC material. Controlling the DC conductivity at a low level is essential to mitigate the risk of having a thermal runaway, especially under type test and pre-qualification conditions. The reason for the focus on DC conductivity when increasing the voltage can be easily understood by setting up the formula for heat generation by ohmic losses in the insulation material:

$$q''' = \sigma E^2 \tag{1}$$

where *q'''* being the power loss density [W/m^3], *σ* the conductivity [S/m] and *E* the electric field [V/m]. By analysing the formula while keeping in mind that the DC conductivity is dependent on both tempereature and electrical field it is clear that the DC conductivity needs to be low and has to be controlled in order to avoid a thermal runaway and subsequent breakdown of the material.

In order to screen different material solutions as EHVDC insulation small scale DC conductivity measurements were used to perform the first selections. In this context it is very important that the measurement set-up and the sample preparation procedure are repeatable and accurate for all type of materials assessed. In addition when measuring on crosslinked materials it is of great importance to control the level of peroxide decomposition products that are present in the material when measured. It is well known that peroxide decomposition products have an influence on the DC conductivity and thus the level need to be controlled in order to measured on a material that is as representative as possible to what is present in a full scale cable. It should also be mentioned that the DC conductivity measurements made in this study are partially degassed samples to mimic the situation present in a cable as good as possible.

In practice small scale testing of DC conductivity of insulating materials is made on compression moulded plaques with a guarded three terminal cell as described in the IEC 62631 (recently replaced 60093) and ASTM D257. To be used at high voltages special care needs to be taken to avoid flashover and protection of test equipment. For practical reasons it is often time consuming to wait until a steady state DC conduction current is established. It was therefore decided to use the current after a specific time as a measure of the DC conductivity at a quasi steady-state. In [8, 9], the robustness of the measurement method was evaluated in a round robin test where nearly identical test setups were used and in [9] it was concluded that the method gave reproducible result, but also that even small variations can lead to deviations in the results. For example it was presented in [10] that the press release film used during sample preparation can significantly influence the results.

Crosslinking characteristics

The shape stability and robustness above the melting point of the material is one of the main differences between a crosslinked and a non-crosslinked material. It is well known that a non-crosslinked material melts and loses its mechanical integrity above its melting temperature. When developing the new EHVDC material with a lower degree of crosslinking compared to conventional XLPE it became a focus area to in detail understand how the long term electrical and mechanical performance were affected by the degree of crosslinking. The presence of the so called memory effect, gives the XLPE its robustness and has earlier been presented for this new material [11]. In addition crosslinking simplifies quality assurance procedures such as hot oil bath.

The crosslinking characteristics of a material can be characterised in several ways: the torque evolution obtained from a MDR (Moving Die Rheometer) using plaque specimens, gel content of already crosslinked samples and the widely accepted hot set test. The latest is very often used to monitor the degree of crosslinking in cable production. The gel content measurement is giving the part of the polymer that is actually contributing to the crosslinked network, i.e. the insoluble part of the polymer. It is measured by extracting the soluble parts of the polymer according to ASTM D2765 – 16.

The hot set test subjects the material for a certain mechanical stress at a given temperature in order to determine the crosslinking properties. However, as described earlier both in this paper and in previous publications [11] this next generation DC XLPE material has a lower peroxide content and crosslinking degree. Since the response of the hot set test is not linear over the whole crosslinking interval the stress exerted on the material needed to be adjusted for the relevant selected crosslinking interval in order to have sufficient accuracy and repeatability. This resulted in a proposed reduction of the mechanical stress from 20 N/cm² to 5 N/cm².

Long term performance

The long term performance of the material is essential since the DC cable constitutes a substantial investment and the life time of such cable needs to be several decades in order to provide the required performance. In addition, any faults on such a cable system could result in loss of transmission possibility in the electrical grid and the economic impact would be significant. Taking all these implications into consideration, it is vital that both mechanical and electrical properties are maintained during the expected life time of the cable system in order

to ensure safe operation and high reliability. In order to verify the long term stress resistance of the EHVDC XLPE insulation material, the resistance to SCG (Slow Crack Growth) was measured as a function of crosslinking level. Non-crosslinked, i.e. thermoplastic LDPE (Low Density Polyethylene) is known to have relatively poor SCG resistance. The so called PENT (Pennsylvania Edge-Notch Tensile) test was chosen to characterise the SCG resistance. This test is described in ASTM F1473 and was originally designed to measure the SCG resistance in materials used for pipes conveying gas or water under pressure. In the PENT test, a notched rectangular specimen is subjected to tensile creep. The primary purpose of the notch is to introduce a tri-axial stress state at the notch tip to ensure a brittle SCG fracture mode. The load is chosen such that the stress at the notch tip is well below the yield stress of the material. The outcome of this test is the time to complete brittle mode failure. An advantage of the PENT test is the fact that the load and technical stress (force / initial load bearing cross sectional area) is constant during the test. This is in contrast to more primitive cracking tests where considerable stress relaxation will occur, thus the mechanical stress will decrease with time and, as a consequence be undefined and relatively low. Materials with high SCG resistance may therefore not reach failure during realistic testing times.
PENT testing was carried out at 70°C and 90°C with the aim to identify crosslinking levels that exhibit sufficient resistance to SCG. Test conditions have been described previously [12, 13].

Tensile creep which is another very relevant measure of the robustness of the material reflects how it withstands strength under external pressure, a situation for example present in accessories. The tensile creep tests according to ISO 899-1:2003 were conducted at several stresses at elevated temperatures, both 70°C and 90°C, to study the time dependent deformation behavior. The strain was measured with a camera by online evaluation of the displacement of the gauge section marks (gauge length of 50 mm here). Also an investigation was made to study the effect of different crosslinking levels on the tensile creep performance.

Finally, defining the thermo-oxidative aging characteristics of the material system is important since the insulation material can be subjected to it during its entire life time. For example, during cable manufacturing, oxygen might be present in low concentrations, but it will be enough to react with the polymer and initiate a degradation process unless the material composition is sufficiently protected by an adequate stabilisation package. The involved degradation mechanisms are well described and reported in the literature [14, 15]. The thermo-oxidative ageing might even continue during cable installation and use depending on service temperature and barrier layer.
Thus accelerated thermo-oxidative ageing tests are essential when designing a new material and the requirements for the insulation materials are stipulated in IEC62067. Nevertheless, these requirements are very often complemented with a life expectancy study as described in IEC60216. Both tests refered to above are good indicators for long term performance. However, they are based on dumbbell shaped samples punched out from a crosslinked plaque or from a cable core sample. Therefore they are not fully representative of the conditions experienced by the insulation material in an actual EHVDC cable since the concentration of oxygen will be very different when ageing a cable sample compared to a dumbbell sample.

In order to better understand the effect of the different sample types on the long term performance thermo-oxidative ageing performance on both ‘traditional’ dumbbells from cross-linked plaques and cable core samples have been compared.

2 mm thick crosslinked plaques were prepared by compression molding by melting at 120°C for 1 min followed by crosslinking at 180°C for 8 min using 573 N/cm^2 pressure. Dumbbells were punched out from these crosslinked plaques and conditioned for 24 hours at 70°C before start of the thermo-oxidative ageing test at 135°C in cell ovens with controlled air circulation. Samples were taken out at the start of the test and after different ageing times until a significant change in the tensile properties had been reached. Carbonyl index as well as melting point and crystallinity were also analysed on these samples.

The cable core samples were extruded and crosslinked on a Catenary Continuous Vulcanisation (CCV) line with a 150 mm^2 aluminum conductor, 10 mm insulation and 1 mm thick inner and outer semiconductive layer respectively. After cable core production 30 cm long cable core specimens, capped at both ends with an aluminum foil to minimise diffusion of oxygen via the cable core ends, were prepared, one for each sample time to be made during the ageing test. These cable cores were conditioned for 24 hours at 70°C before start of the thermo-oxidative ageing that was performed in an oven at 135°C. Cable cores were taken out for testing at the start of the test as well as after different ageing times up until 365 days had been reached. From these cable cores 2 mm thick dumbbells were prepared according to IEC 60811-1-2:1985 from the middle part of the insulation layer for tensile testing. Carbonyl index, melting point and the degree of crystallinity were analysed on a lathed thin film taken from the middle part of the insulation layer.In addition also the key electrical properties, DC conductivity and space charges, were monitored as well as a function of ageing time. Both these electrical tests were made on thin lathed film samples taken from the middle part of the insulation layer. These tests gave important information whether the key electrical properties were affected by the thermo-oxidative ageing before any alteration could be seen in the mechanical properties.

THE RESULTING PROPERTY PROFILE

As discussed earlier in this paper it is important that electrical, mechanical and long term properties are appropriate for the requirements that the EHVDC transmission on levels above 320 kV is imposing on the material.

In order to visualise the interaction and balance between the electrical and mechanical properties as a function of the degree of crosslinking, while using the same base polymer, a schematic profile of these key properties is presented in Figure 1. The X axis in this comparison is characterised by the max torque from MDR measurements and the Y axis is describing the different key properties in arbitrary units. The shaded part to the right in the figure is the region illustrating the property relationship for a material with conventional crosslinking degree which is commercially used for voltage up to 320 kV.

In addition to the minimisation of charge carrier which was the basis for the development, it is also well known that the content of peroxide decomposition products is influencing the DC conductivity. So in order to reduce the DC conductivity further even this effect needed to be assessed. Figure 1 is showing that DC conductivity is decreasing with the degree of crosslinking. In addition, decreasing the peroxide content is not only reducing the DC conductivity but also potentially means a shorter degassing time. The lower peroxide content also reduces the risk of scorch, i.e. premature crosslinking formation during extrusion.

In Figure 1 three different measures of crosslinking degree are shown. The reason for using different methods is that they are not exactly measuring the same physical phenomena of the material. The response in the hot set test is seen to be strongly dependent on the mechanical test stress exerted on the sample. In Figure 1 the result of using two different mechanical test stresses are shown 5 and 20 N/cm² respectively. It is clear that only a part of the crosslinking interval studied can be measured with sufficient accuracy using hot set. In order to obtain reliable and accurate measurement values the mechanical stress should be such that the hot set values are situated in the low slope region. In contrast, the gel content is measureable over almost the entire crosslinking interval although it is not linearly dependent on the max torque value either. The non-linearity is due to the different crosslinking reactions occurring during the crosslinking process and is dependent on the network size, where the first stage, present at lower degrees of crosslinking, is predominantly intermolecular reactions. The second stage is a balance between inter and intramolecular reactions while the last stage at higher degrees of crosslinking is predominantly intramolecular reactions. Worth noting is that the high slope regions in the hot set measurements are not coinciding with any substantial drop in gel content and hence merely are an effect of the measurement method rather than a significant change of the material structure. Since the crosslinking has a significant effect on the mechanical performance, it is interesting to observe that the steep increase in SCG performance in PENT seen in Figure 1 is coinciding with the onset of the gel content. The SCG resistance increases significantly by introducing chemical crosslinks. In fact, materials with an intermediate crosslinking level have such a high SCG resistance, more than 2 times higher compared to the conventional material, that the testing was stopped after ~12000 hours. Thus, these materials have exceptionally high SCG resistance, significantly higher than an XLPE material with conventional crosslinking level in the striped shaded region to the right. The poor SCG resistance of thermoplastic LDPE is most likely a result of relatively low molecular weight (i.e. low entanglement level) and tie chain concentration. However, as crosslinks are introduced, the molecular weight increases, leading to higher concentration of entanglements and tie chains. However, it is seen that at high crosslinking degrees the SCG performance goes down; several factors interact here. To start with crosslinking occurs in the molten state which reduces crystallinity. As a result, the conventional XLPE has the lowest level of crystallinity of all the studied materials. A lower crystallinity level makes it more challenging to carry mechanical load since this is mainly done by the polymer crystals. Furthermore, crosslinking in principle also restricts the ability to plastically relax local stresses at the crack tip. As a result the effective stress at the crack tip can become higher which would facilitate crack propagation and make the material more vulnerable to damage. Also the lower strain creep resistance as depicted as creep modulus is primarily dependent on the crystallinity.

Combining the mechanical and electrical properties one can see that there is a region grey shaded in Figure 1 where the properties are balanced in such a way that both the electrical and mechanical fulfil the required property profile. This includes a crosslinking level based on gel content determination suited for performing quality assurance tests (such as hot oil test), mechanical properties exceeding the conventional materials and a low DC conductivity ensuring a low risk of thermal breakdown at extra high voltages.

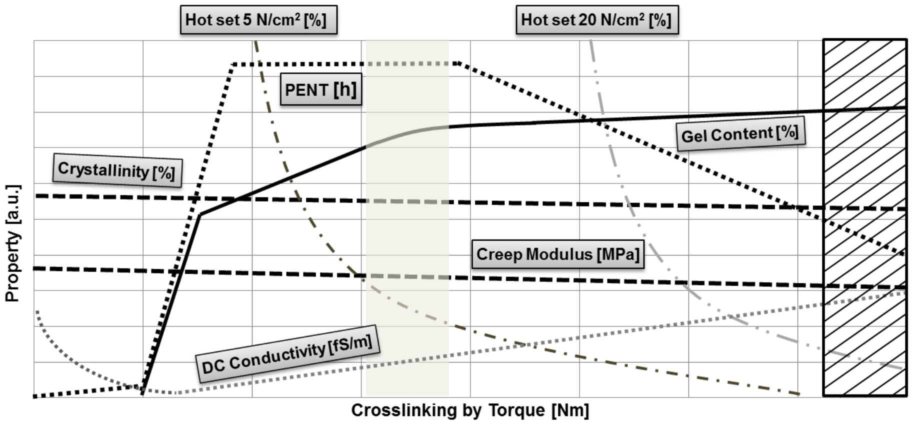

Figure 1 The balancing of mechanical and electrical properties of the material schematically drawn at operating conditions

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Thermo-oxidative ageing performance

Figure 2 represents the tensile properties, presented as stress and strain at break, for both types of samples. A significant difference can be seen when comparing the two sample types. When ageing cable core, no significant change of tensile properties can be noticed after one year ageing at 135°C whereas sample from the plaques show significant reduction of tensile properties after close to 80 days of ageing.

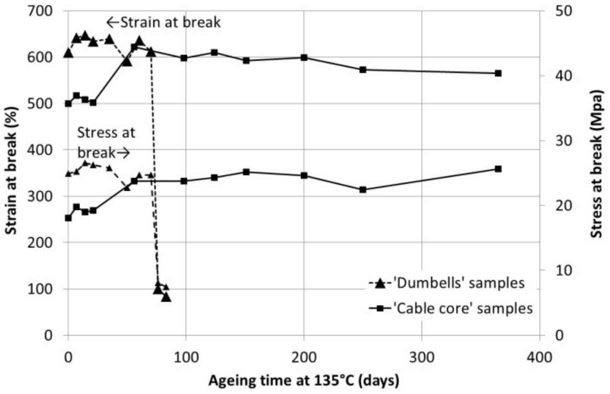

Figure 2 Tensile properties as function of ageing time at 135 °C for both dumbells and cable core samples

The main reason for this difference is the level of oxygen present and the resulting oxidation that occurs in the samples. The access and diffusion of oxygen will be easier and shorter for dumbbells from plaques than for cable core, that contains both a thicker insulation layer and layers of semiconductive material on each side, leading to a faster oxidation rate as depicted by the carbonyl index in Figure 3 and Figure 4. It is also evident that when the oxidation reaches very high levels reactions such as chain scission and formation of structures leading to a significant decrease of the melting point and degree of crystallinity occur, Figure 3. These irreversible structural changes of the material are coinciding with the change of mechanical properties.

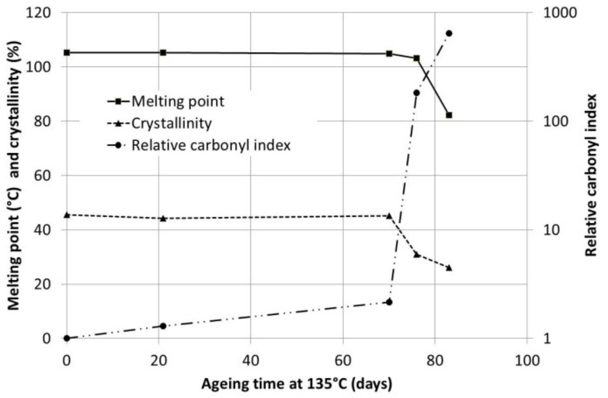

Figure 3 Thermal properties and relative carbonyl index as function of ageing time at 135 °C for dumbells samples

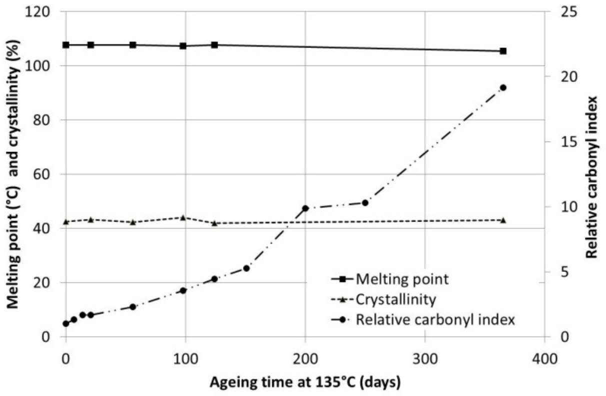

Figure 4 Thermal properties and relative carbonyl index as function of ageing time at 135 °C for cable core samples

In the aged cable core samples there is a gradual increase of the carbonyl index but at a signifantly lower level than in the dumbbell samples. The 365 days of ageing at 135 °C does not lead to any change of the thermal properties.

As explained earlier in this paper, beside mechanical properties control of electrical properties is key. Therefore it was of importance to understand if thermo-oxidative ageing could affect them. This would also give a very good indication whether it is the electrical properties or the standard IEC methods for ageing measurement based on mechanical properties that sets the ageing limitation. DC conductivity and space charge were measured at 70°C and 30 kV/mm for the cable core samples being most representative for the real case. For these measurements, a thin film was lathed from the middle part of the insulation layer.

Figure 5 represents the charge density as a function of the position in the thin film reference sample before ageing, measurement taken after 2 hours. There is no charge build-up in this sample before ageing. The field enhancement factor (FEF) was also calculated and is presented as a function of the ageing time at 135°C at both ground and high voltage electrode (HV) in Figure 6 together with the DC conductivity and the relative carbonyl index.

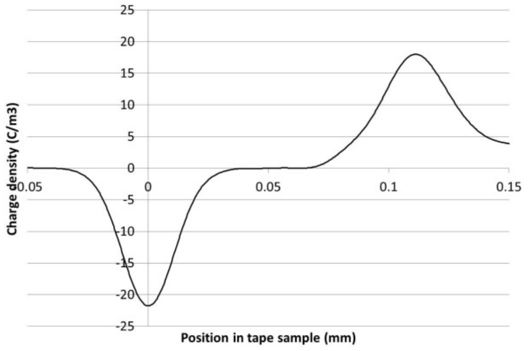

Figure 5 Charge density profile before ageing at 135°C of the middle part of the insulation layer in the cable core

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First of all the significant decrease of the DC conductivity between the un-aged and samples that have been aged for very short times is due to the removal of the peroxide decomposition products that were still present in the cable core when starting ageing. Secondly, it can be noticed that DC conductivity which was one of the key electrical properties in this development is not affected by the increase in oxidation that takes place in the studied time interval. It stays constant and on a very low level during the entire ageing time. A slight increase of FEF can be noticed indicating that only a small amount of charges are accumulated during ageing. However this FEF increase is minor compared to the increase of carbonyl index. Thus, it can be concluded that the thermo-oxidative ageing resulting in the formation of carbonyl groups is not detrimental for the key electrical properties.

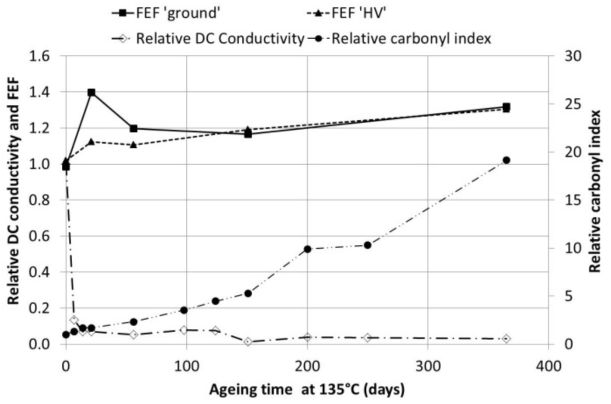

Figure 6 DC conductivity, FEF and relative carbonyl index as function of ageing time at 135°C of the middle part of the insulation layer in the cable core

CONCLUSIONS

In conclusion; the target was to increase the power transmission capacity by increasing the voltage, where it was neccesarry to maintain a low and controlled DC conductivity to reduce the risk of thermal runaway and still have the mechanical properties needed for the application. It has been shown that the key electrical property, DC conductivity, is balanced with the mechanical properties. In addition one can see that the key properties both in terms of electrical and mechanical properties remain stable after ageing under the conditions applied for this investigation. In an earlier publication it was also shown that the same is valid for the crosslinking properties [13]. This also implies that the property balance profile shown in Figure 1 is also valid after cable ageing at 135°C for 365 days.

To verify the balanced properties it has been shown that this is a robust material that fulfils the property profile needed for passing various type tests and pre-qualification tests at 525 kV and more recently at the record level of 640 kV according to Cigré TB496.

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