Challenges and opportunities with interfaces and materials for HVDC cable systems

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ABSTRACT

HVDC cable technologies will play a critical part in integrating renewable generation sources into the electrical power systems of the future. Here, we first consider how HVDC cables have evolved to the present time, with reference to the adoption of extruded insulation systems. In particular, we discuss the advances by which recently reported dramatic increases in rated voltage (up to 640 kV) have come about. We then describe a simulation approach for assessing the feasibility of developing cable systems for use at even higher voltages; this suggests that existing insulation materials may be approaching their performance limit, when both the internal electric field and thermal factors associated with heat dissipation in the conductor are jointly considered. Finally, some potential next-generation cable insulation systems are described, which address the performance gaps identified in the simulation.

KEYWORDS

Materials design; crosslinked polyethylene; numerical simulation; thermoplastic insulation.

INTRODUCTION

It is now widely accepted that the combustion of fossil fuels results in changes in atmospheric chemistry that are having an increasing impact on the climate of our planet. Nevertheless, the demand from both developed and developing economies for energy continues to grow, with the U.S. Energy Information Administration's International Energy Outlook 2016 (IEO2016) reference case projecting that global generation of electricity will increase from $2.2x10^{13}$ kWh in 2012 to $3.7x10^{13}$ kWh in 2040 [1]. While fossil fuels will, for the foreseeable future, continue to make a major contribution to meeting this demand, the role played by renewable sources will grow, which will require electrical power systems to evolve to accommodate them.

Increased reliance on renewable sources of electricity generation will, for a number of reasons, require the adoption of new power transmission technologies. First, renewable generation will in general need to be located at sites that are remote from major centers of demand (e.g. off-shore wind farms; hydro-generation in mountainous areas). Second, many renewable sources of generation (e.g. wind and solar) are intrinsically intermittent, which will lead to the interconnection of national power systems to form international supergrids, whereby massive power flows over long distances will become, increasingly, the norm. High voltage direct current (HVDC) transmission will be essential in facilitating this and, while overhead lines have much to recommend them in many circumstances, such a solution is impractical where connections involve crossing the sea or where the perceived environmental impact of overhead lines is unacceptable. This problem is well illustrated in Germany, where low public acceptance of overhead power lines means that the Südlink project will require the installation of a 700 km, 500 kV underground HVDC link from the northern seaboard to demand centers in the center and south of the country, in order to integrate offshore wind generation. Indeed, in total, TransnetBW GmbH has estimated that Germany will require new HVDC transmission corridors with a total length of between 2600 and 3100 km and with a total transmission capacity 12 GW [2]. While many HVDC subsea systems have been installed successfully, such underground systems on land pose many challenges, many of which relate to the design of the cable and the choice of the insulation system.

EVOLUTION OF HVDC CABLES

Many different HVDC cable technologies have been developed in preceding decades and have been successfully deployed around the world. Although the majority of well-established HVDC cable systems currently in service are based on paper/oil or mass impregnated insulation systems, the complexity of manufacture, weight and limited operating temperature of such systems are contributory factors in driving the current interest in HVDC cables based upon extruded polymeric insulation.

It is generally acknowledged that the world's first HVDC transmission system using cable designs based on extruded polymeric insulation (crosslinked polyethylene – XLPE) was used to connect the Swedish island of Gotland (50 MW; 80 kV; 70 km) in 1999. Incremental advances in the following years led to incremental increases in both the rating and operating voltage of such systems. Table 1 illustrates this progressive evolution in terms of ABB's HVDC Light technology [3]. However, recent years have witnessed a remarkable acceleration in the development of such systems, with companies such as ABB, and latterly NKT, reporting major advances in HVDC XLPE technology. In 2014, ABB reported on a new 525 kV HVDC extruded cable system with a power rating range of up to 2.6 GW for use in both subsea and underground applications [3]. In 2017, the same basic material technology was used by NKT to produce a 640 kV XLPE-insulated HVDC cable which, NKT indicates, differs from its 525 kV ABB predecessor only in terms of design optimization, process parameters and through the implementation of more sophisticated quality assurance measures [4].

Table 1: Extruded DC (HVDC Light) cable systems from ABB submarine and land based installed cables [km] and country and year of installation (adapted from [3]).

Project	Country	Year	Voltage *[kV]*	Submarine *[km]*	Land *[km]*
Gotland	Sweden	1998	80	0	140
Directlink	Australia	1999	84	0	390
Murraylink	Australia	2002	150	0	360
Cross Sound	USA	2002	150	83	0
Troll A	Norway	2004	60	284	0
Estlink	Estonia-Finland	2006	150	150	62
BorWin1	Germany	2009	150	266	155
EWIP	Ireland-UK	2012	200	372	152
DolWin1	Germany	2013	320	170	187
SouthWest link	Sweden	2014	300	0	797
NordBalt	Sweden-Lithuania	2015	300	800	100
Aland-Finland	Finland	2015	80	318	0
DolWin2	Germany	2015	320	99	183

FROM MATERIALS TO CABLES

The radical advances in XLPE-insulated HVDC cable designs introduced above that have emerged in recent years are based upon novel material systems, which include both insulation and complementary semiconducting (semicon) screen systems. As such, it is worth posing the question: what is innovative about these systems that has led to such rapid progress? A key factor appears to be Borealis' development of their Borlink^{TM} materials, which are described as exhibiting an optimized combination of chemical, mechanical and electrical properties, with ABB highlighting high breakdown strength and very low DC conductivity as being key characteristics.

Space Charge and Impurities

XLPE has been widely used for many decades as the insulation in high voltage cables, because of the thermo-mechanical benefits that result from crosslinking. Crosslinking of low density polyethylene (LDPE) with dicumyl peroxide (DCP) has been studied for many years [5], as has the impact of retained crosslinking by-products on key electrical characteristics. For example, Hirai et al. [6] considered the impact of a number of DCP decomposition products on charge transport dynamics in PE and concluded that cumylalcohol acts as a trap for charge carriers while acetophenone and α-methylstyrene act to assist carrier transport. Conversely, a complementary theoretical study of the effect of such impurities on charge trapping in PE suggested that α-methylstyrene should be most strongly related to trapping phenomena. While the detailed results of such studies may differ, the key conclusion is nevertheless equivalent: retention of the small molecular by-products of DCP decomposition will affect space charge formation which, in turn, must increase the local field and thereby reduce service life.

While the crosslinking process itself is a source of impurities, it is not alone in this regard and a number of studies have considered the influence that changes in semicon formulation exert on electrical characteristics of the neighboring insulation. In 2010, Nilsson and Boström [7] described an important study of the influence of semicon formulation on space charge accumulation. Specifically, this work involved formulations that differed with respect to both the base polymer used and the cleanliness of the carbon black. Elemental analysis indicated that while their furnace black contained 100 ppm of sulfur (total impurities ~160 ppm), this was not present in the acetylene black (total impurities ~40 ppm – ~3 ppm sulphur). While replacement of the furnace black with acetylene black was found to reduce space charge accumulation, replacement of the polar ethylene/butyl acrylate (EBA) base polymer with non-polar systems was found to yield more significant benefits. Based upon Fourier transform infrared (FTIR) data, it was suggested that this was linked to migration of low-molar mass species from the polar semicon into the insulation. This conclusion is in line with earlier work [8] in which peelings, ~100 µm in thickness, were cut from an XLPE-insulated cable sample and analyzed by FTIR, such that the chemical composition as a function of radial position could be obtained. Variations in the concentration of carbonyl groups from ester groups originating in the copolymers used in the semicon, was used to infer diffusion of low molar mass molecular fractions from the semicon into the XLPE; DC breakdown testing of the peelings showed a good correlation between reduced DC breakdown strength and the intensity of the absorbance peak at 1735 cm^{-1}.

Advances in XLPE Insulation

While it would be unreasonable to ascribe the recent dramatic advances in XLPE-insulated HVDC cable technology to a single factor, it is evident from material published by both ABB and Borealis that a major, if not dominant, contributory factor is the LDPE resin itself. Reference to the patent literature reveals a number of significant changes that relate to the active design of the molecular architecture, specifically to generate material systems that are targeted at HVDC cable applications. The Borealis patent EP3190152 (*A Cable and Production Process Thereof* – published in July 2017) [9] is one such. A key element of this appears to be the inclusion of a degree of unsaturation within the molecular architecture, an innovation which would seem to be related to increasing the ease of peroxide crosslinking. Certainly, such a strategy is consistent with the notion of minimising unwanted peroxide crosslinking by-products and, therefore, would be consistent with the requirements of advanced HVDC cable insulation systems.

Advances in Semicon Formulation

It is apparent from the above discussion that the semicon is also a potential source of impurities that can migrate into the insulation with adverse consequences. As such, a number of steps can be envisaged to minimise such effects, which include the use of high purity carbon blacks and replacement of conventional polar co-polymers with appropriate non-polar systems. This strategy is well exemplified in patent WO2017089201 (*Semiconductive Polyethylene Composition*, Borealis AG, published June 2017) [10], where one of the stated aims is the formulation of a semicon system that will lead to “excellent space charge performance to ensure good DC properties in a cable”. The innovation described is to base the semicon on very low density copolymers of ethylene and an α–olefin (so-called plastomers), where the required combination of electrical, mechanical and rheological properties is achieved by suitable selection of the carbon black loading level combined with blending of different plastomer grades.

TOWARDS HIGHER VOLTAGE CABLES

Although the advances made in recent years in increasing the voltage and ampacity of XLPE-insulated HVDC cables are impressive, current HVDC overhead lines are operating at up to 1.1 MV and, as such, cables still lag some way behind. While it is possible to approach this through an incremental approach in which design considerations, material processing and polymer characteristics are iteratively refined, here, we describe a fundamentally different approach to the problem, which is based upon three distinct steps:

- Numerical simulation is used to explore the available parameter space.
- Required material characteristics and performance gaps (relative to current materials technologies) are identified.
- Material systems are explicitly designed to address these deficiencies.

HVDC CABLE SIMULATION STUDIES

The feasibility simulation described here was based on algorithms for electric field calculations in DC cable insulation, using considerations relating to failure statistics obtained from laboratory accelerated life testing on cable models, combined with the relevant dimensional effect expression needed to convert from sample testing to full-size cable design.

The cable insulation design was divided into two steps, which interact one with the other:

a) Electrical-statistical design, aimed at defining the insulation geometry that is necessary to ensure the required electrical performance;
b) Thermal design, which is aimed at verifying that the maximum temperature inside the insulation does not lead to overheating (thus life reduction through Arrhenius law) or even thermal runaway.

Electrical-statistical Design

The major issue here concerns the electric field profile in a DC cable, which can change significantly with the temperature gradient that evolves across the cable insulation during operation. Consequently, designing the cable insulation thickness based on a mean field (as under a uniform field distribution) may bring a level of approximation that poorly describes the likely effect of the actual spatial distribution of field on cable life. Secondary issues are (a) that a statistical approach is needed to estimate design life from a given failure probability and (b) dimensional effects associated with extrapolating from laboratory specimens to fill-size cable must be taken into consideration.

If E_{MAX} is the maximum field, which depends on ΔT and R_{id} (temperature drop and internal insulation radius, respectively), the limiting electrical condition for cable feasibility is:

$$E_{MAX}(\Delta\mathrm{T}, R_i) = E_3(R_{id}) \qquad (1)$$

where E_3 is the expected design field providing the desired life at the chosen failure probability. This equation allows the internal radius of the cable insulation to be determined. To be solved, eq. (1) needs to be coupled with an equation correlating the temperature drop, ΔT, with the internal radius, R_{id}, which is the Fourier thermal equation. This is considered below.

Thermal Design

The aim of the thermal design is to verify if the temperature distribution inside the cable is acceptable given the requirements. Under DC conditions, we assume that the only heat source is represented by the Joule losses of the internal conductor, $R_{cc}I^2$. Depending on the insulating material’s maximum operating temperature and the temperature of the cable’s environment, the cable ampacity can be obtained, the maximum ΔT estimated and the maximum electric field in the insulation calculated.

Feasibility

Feasibility concerns the need of a design to conform to eq. (1). If an internal radius, R_{id}, able to satisfy eq. (1), exists, then cable manufacture is feasible and it is possible to start the thermal design. Otherwise, it is necessary to restart the design with a larger size of extruder and/or different insulation parameter values.

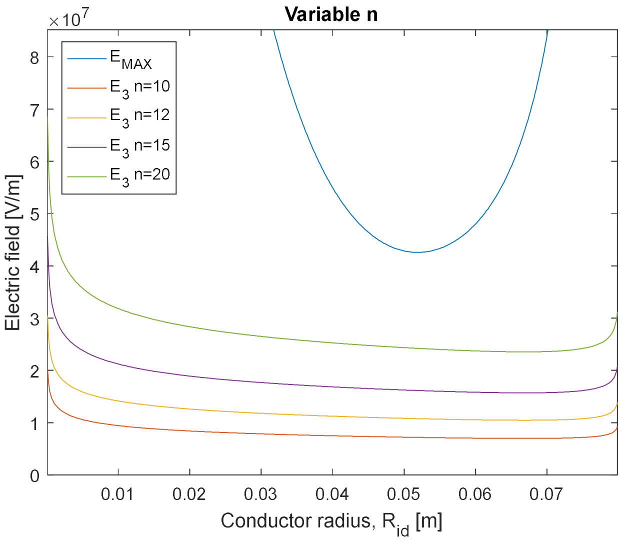


Fig. 1. Example contour (feasibility) plots for E_{MAX} and E_3 for different values of the voltage endurance coefficient, *n*.

Fig. 1 contains exemplar contour plots summarizing a design feasibility exercise for a polymeric DC cable of 800 kV and 3 kA, using typical parameters valid for high voltage alternating current (HVAC) grade XLPE. The variable parameter is the voltage endurance coefficient, *n*, which is the inverse of the life line slope. As can be seen, for none of the *n* values considered does the consequent curve intersect with the curve indicating E_{MAX}; thus, eq. (1)

is not satisfied. This means that the cable is not feasible with the chosen parameter values and the performance-rating specifications.

Based on the results of the simulations, it appears that the feasibility of extra high voltage DC (EHVDC) polymeric insulated cables may be questionable considering the technologies and the characteristics and properties of the insulation materials that, currently, are most commonly used in extruded polymeric cables, XLPE in particular.

There is a need for a very high breakdown strength and large value of *n*, also, in relation to the cable length (dimensional effect). In order to increase cable length, a major issue is the value of the shape parameter of the Weibull distribution of breakdown strength and failure times, which must be as high as possible. This reflects the need to have maximum homogeneity of the insulation, placing demands on both the material and the extrusion process.

The extruder for an EHVDC cable would have a larger diameter than those currently used to cover the voltage range up to 400-500 kV, because the maximum electrical field is a challenge that materials cannot cope with at present. Regarding this, the activation energy of the conduction process in the insulation has to be lowered as much as possible, to reduce the dependence of the conductivity on the temperature gradient (thus on cable ampacity).

Also, the space charge accumulation threshold will become an issue, because if the cable has to run with the required design reliability, the maximum electrical field must be lower (at the operating temperature) than the threshold for space charge accumulation. Therefore, the capability of the insulating material to store space charge at very high field will be a fundamental issue for the development of EHVDC cables.

The above considerations may introduce the need to investigate nanostructured materials and/or polymeric materials different from XLPE (such as thermoplastic materials). In addition, if the operating temperature can be raised above the present limit established by the thermal characteristics of XLPE, i.e. 90 °C, an increase in ampacity will be favored. In this case, even more, the need to control the activation energy of the conduction process (to reduce the variation of conductivity as function of thermal gradient in the dielectric and, thus, the maximum field value) will become critical for the insulating polymer candidates chosen for HVDC applications. Addressing all these requirements can only be achieved through the development of new materials, some of which are currently emerging.

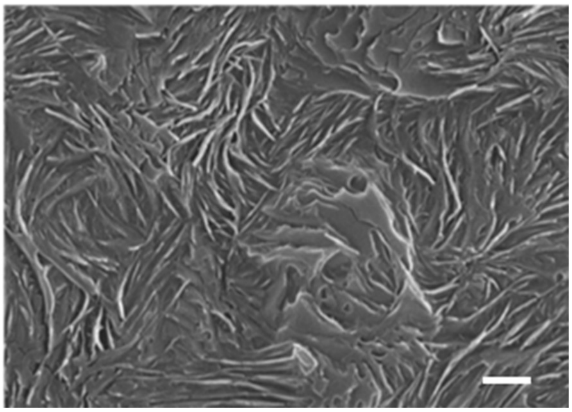
THERMOPLASTIC HVDC INSULATION

In 2016, Prysmian issued a number of announcements relating to the use of its thermoplastic P-Laser technology in HVDC applications, which culminated in September with the launch of a 600 kV HVDC cable system. As described in the related CIGRE publication [11], this material facilitates an increase in cable operating temperature up to 130 °C, which provides increased flexibility to network operators. Also, by eliminating the need for crosslinking, the insulation system is intrinsically free of the crosslinking byproducts discussed above. Although complete details of the P-Laser insulation system have not been published, it is described as being a high performance thermoplastic elastomer [12], which related patents also indicate that the concept is based upon a combination of propylene-based polymers plus a dielectric liquid [13].

Designing Cable Insulation Systems

Cable insulation materials are required to meet a range of properties, that include electrical, mechanical and thermal factors. As such, designing systems to meet the requirements of particular applications is far from trivial. However, from the HVDC perspective, the importance placed upon reduced impurity levels makes thermoplastics highly attractive; while only Prysmian has, thus far, brought a thermoplastic-insulated cable to market, it is very clear from the patent literature that many other cable companies are active in this space.

A key feature of thermoplastic polymers is their morphological complexity, which involves the formation of complex hierarchical microstructures that generally include electrically weak regions [14]. The nature of the materials design challenge is well illustrated in a number of publications published by Hosier et al. [15, 16], which considered the effect of changes in morphology on the short-term breakdown strength of polyethylene. In this study, high density polyethylene (HDPE) was added to LDPE and the blend composition, combined with different thermal treatments, were used as a means of varying the microstructure of the system. This work showed that


(a)

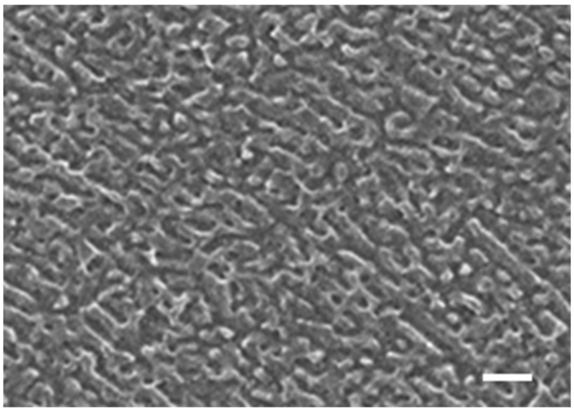

(b)

Fig. 2. Scanning electron micrographs (scale bars 1 μm) comparing the designed morphology of two blend systems: (a) 20% HDPE and 80% LDPE; (b) 50% isotactic polypropylene and 50% of a propylene/ethylene copolymer

systems in which crystallization results in a space-filling array of thick lamellar crystals (here, primarily composed of HDPE) can exhibit attractive combinations of electrical and mechanical properties, which include increased breakdown strength, good low temperature flexibility and high temperature mechanical integrity. Such a morphology is shown in Fig. 2a.

While HDPE/LDPE blends such as those described above illustrate basic principles well, extending the concepts to polypropylene in order to exploit the higher melting temperature of this polymer – as in the case of Prysmian's P-Laser – is far from trivial. Nevertheless, the Suscable I collaborative project, involving the University of Southampton, Gnosys Global, Dow Chemicals and National Grid, successfully built on earlier academic work on blends of isotactic polypropylene (iPP) and various propylene-based copolymers [17] to develop novel blend systems that exhibited excellent combination of properties obtained from laboratory plaque samples, which were retained when extruded into mini-cables (see Fig. 2b). Progressive DC stress testing of 6 m lengths showed that, while XLPE insulated mini-cables all failed at applied DC voltages in the range 168-224 kV, none of the mini-cable specimens based on the designed propylene-based blend failed before the maximum voltage of 400 kV was reached, which corresponds to maximum electric field within the insulation of more than 120 kVmm^{-1} [18]. Subsequent work has sought to extend these concepts by up-scaling to a pseudo-commercial medium voltage cable design (Suscable II); increased thermal conductivity for increased cable ratings (CableSure).

Suscable II was conceived to produce a medium voltage AC (MVAC), high operating temperature cable system, based upon polypropylene blends. Such systems would not require crosslinking and, consequently, would be very clean with no-crosslinking by-products. This development has now been achieved and it will be used to support HVAC and HVDC cable development based on the same technology. More complex polypropylene blend formulations have been developed beyond those patented in Suscable 1 [19]. These materials have excellent (HVAC) and HVDC performance and are expected to feature in a new HVDC cable insulation system, which combines a new semicon system that works effectively with the insulation system. The additional attraction of this development is that the polymer components required for the insulation system can be sourced from multiple suppliers provided they are appropriately qualified.

However, an intrinsic issue with any cable insulated with polypropylene is the reduced thermal conductivity of this polymer. Indeed, Pilgrim et al. [20] analyzed the impact of different insulation properties on cable rating and overall power losses for a high voltage AC cable design and concluded that thermal conductivity was of most significance in determining these. As such, increasing thermal conductivity can be of great practical significance and, therefore, a massive body of research exists in this area, the majority of which has involved the addition of particulate fillers. While this strategy has been shown to be a viable means of producing significant increases in thermal conductivity, this invariably appears to require the formation of percolating filler structures. While this is very reasonable in that it is explicable in terms of minimization of phonon scattering at particle/matrix interfaces, the consequences, from a dielectric perspective, are severe. For example, the problem is well illustrated in the recent publication by Chi et al. [21], who used applied magnetic fields to induce ordering in iron oxide/polyethylene nanocomposites. While the result was a maximum increase in thermal conductivity of 46% on including 7 vol.% of magnetically ordered nanofiller, the addition of just 1 vol.% of the filler resulted in an increase in electrical conductivity of three orders of magnitude. To increase thermal conductivity whilst maintaining excellent insulation characteristics is a major challenge.

Nevertheless, recent work at the University of Southampton has revealed a previous unreported form of behavior for systems based upon hexagonal boron nitride (hBN), where an increase in thermal conductivity of more than 60% has been accompanied by an increase in breakdown strength in excess of 20% [22]. These preliminary results are currently being refined in the CableSure project, involving the University of Southampton and Gnosys Global, through optimization of the hBN surface chemistry both to enhance dispersion within the polymer and to minimize phonon scattering at matrix/filler interfaces. Combining these concepts with those described above in connection with our Suscable II developments will produce a new generation of HVDC cable insulation systems characterized by increased breakdown strength, reduced electrical conductivity and space charge accumulation, increased maximum operating temperature and increased thermal conductivity compared with current state-of-the art systems.

CONCLUSIONS

The need for long-distance transmission of large quantities of electrical power as remote sources of renewable generation are incorporated into national power systems, combined with the need to connect these together to form trans-continental supergrids, is driving the need for novel HVDC technologies, including cables that are able to operate at higher voltages and ampacities. In recent years, two competing approaches have begun to emerge and, while these employ very different polymer systems, a critical feature of both the ABB/NKT/Borealis XLPE and Prysmian P-Laser HVDC strategies for cables capable of operating above 600 kV, is minimization of the impurities that lead to space charge accumulation and electrical conduction. That is, both of these strategies are based upon advances in materials. Looking forward, we propose that future advances will need to continue to embrace a unified approach in which cable design is used to identify material performance gaps and, based upon this, novel material solutions will need to be actively designed. This approach has been exemplified here through an initial feasibility evaluation of a prototype 800 kV, high ampacity EHVDC cable. This simulation suggests that established materials technologies may be close to their ultimate performance ceiling and that radically new systems will shortly be needed, such as the propylene-based blend and hBN nanocomposites that we describe.

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GLOSSARY

DCP: Dicumyl peroxide
EBA: ethylene/butyl acrylate
EHVDC: Extra high voltage direct current
FTIR: Fourier transform infrared
hBN: Hexagonal boron nitride
HDPE: High density polyethylene
HVAC: High voltage alternating current
HVDC: High voltage direct current
iPP: Isotactic polypropylene
LDPE: Low density polyethylene
MVAC: Medium voltage alternating current
PE: Polyethylene
XLPE: Crosslinked polyethylene