Challenges and opportunities with interfaces and materials for HVDC cable systems

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Abstract

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**JICABLE HVDC'17 KEYWORDS :** Materials design; crosslinked polyethylene; numerical simulation; thermoplastic insulation. **DOSSIER 2 86 Z**

Challenges and opportunities with interfaces and materials for HVDC cable systems Gian Carlo Montanari; University of Bologna, (Italy), giancarlo.montanari@unibo.it Alun S. Vaughan; University of Southampton, (UK), asv@ecs.soton.ac.uk Peter Morshuis, Solid Dielectric Solutions, (The Netherlands), peter.morshuis@dielectrics.nl Gary C. Stevens, Gnosys Global, (UK), g.stevens@gnosysgroup.com

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 2.2x1013 kWh in 2012 to 3.7x1013 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. 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.

ABSTRACT

Challenges and opportunities with interfaces and materials for HVDC cable systems 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 formerly 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]. 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 BorlinkTM 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 having the impact to retain 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 _-methylstyrene act to assist carrier transport. Conversely, a complementary theoretical study of the effect of such impurities on charge trapping in PE suggested that _-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 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]). JICABLE HVDC’17 DOSSIER 2 Z 88 Challenges and opportunities with interfaces and materials for HVDC cable systems 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 formerly 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]. 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 BorlinkTM 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 having the impact to retain 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 _-methylstyrene act to assist carrier transport. Conversely, a complementary theoretical study of the effect of such impurities on charge trapping in PE suggested that _-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 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]).
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 _-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: s. UMERICAL SIMULATION IS USED TO EXPLORE THE AVAILABLE parameter space. s 2EQUIRED MATERIAL CHARACTERISTICS AND PERFORMANCE GAPS (relative to current materials technologies) are identified. s -ATERIAL 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 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 REE N°1/2018 Z 89 Challenges and opportunities with interfaces and materials for HVDC cable systems 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 full-size cable must be taken into consideration. If EMAX E is the maximum field, which depends on X 6T and 6 6 Rid (temperature drop and internal insulation radius, respectively), the limiting electrical condition for cable feasibility is: (1) where E3 E 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, 6T 6 6 , with the internal radius, T T Rid , 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, Rcc I2 . 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 6T 6 6 estimated and the maximum electric field T in the insulation calculated. Feasibility Feasibility concerns the need of a design to conform to eq. (1). If an internal radius, Rid, d d 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 contains exemplary 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 EMAX E ; 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. Figure 1: Example contour (feasibility) plots for EMAX E and X E3 E for different values of the voltage endurance coefficient, n. JICABLE HVDC’17 DOSSIER 2 90 ZREE N°1/2018 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
magnitude. To increase thermal conductivity whilst maintaining excellent insulation characteristics is a major challenge. Nevertheless, recent work at the
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
applied magnetic fields to induce ordering in iron oxide/polyethylene nanocomposites. While the result was a maximum increase in thermal conductivity of 46%
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
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
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
insulation system. The additional attraction of this development is that the polymer components required for the insulation system can be sourced from multiple
polypropylene blend formulations have been developed beyond those patented in Suscable 1 [19]. These materials have excellent HVAC and HVDC
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
based upon polypropylene blends. Such systems would not require crosslinking and, consequently, would be very clean with no- crosslinking by-products.
composed of HDPE) can exhibit attractive combinations of electrical and mechanical properties, which include increased breakdown strength, good low
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 1300 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], of 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 systems in which crystallization results in a space-filling array of Figure 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. REE N°1/2018 Z 91 Challenges and opportunities with interfaces and materials for HVDC cable systems 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 not that simple. 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 kV/mm-1 [18]. Subsequent work has
sought to extend these concepts by up-scaling to a pseudo-commercial medium voltage cable design (Suscable II); it resulted in 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 previously 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 amperages. In recent years, two competing approaches have begun to emerge and, JICABLE HVDC’17 DOSSIER 2 92 Z

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

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