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Abstract: This study sets out to discuss the challenges that need to be addressed effectively to facilitate the adoption of long distance high-voltage and ultra-high-voltage direct current (UHVDC) power transmission cables. As in the alternating current case, the desire to minimise the losses has involved the use of increasingly high transmission voltages, which presents particular problems where UHVDC cables are concerned. Specifically, this study presents the case for a novel, integrated approach to the problem, which links three distinct aspects of the problem, namely: (i) cable ratings and network operability; (ii) cable design and constituent insulating material requirements; and (iii) potential strategies for the design of novel insulation materials, where the required properties are actively 'designed in'. The study concludes that the impact of these factors acting in concert on network operation/performance requires a more integrated approach to the problem than has traditionally been the case. A number of complementary strategies for the development of novel material technologies and UHVDC cable designs are required that can meet the service performance and ultimate service lifetimes expected for new network applications.

1 Introduction

It can be argued that the modern world began around 1700 in the West Midlands of the United Kingdom as a result of the endeavours of entrepreneurs, including Abraham Derby. The critical change that can be traced to this time and place was the start of iron production on an industrial scale and the consequent birth of the Industrial Revolution. The key transformative element was the change to iron-making that resulted from the substitution of charcoal by coke [1]. That is, from a renewable resource to one based on fossil fuels, and the dominant position of fossil fuels has been a key feature in mankind's development ever since. However, this situation is unsustainable, initially, it was thought, because of the finite nature of such resources and, more recently, through general acceptance of the impact that the continued use of fossil fuel combustion is having on the planet's atmosphere. Despite this, global demand for energy is projected to grow in coming decades. For example, in the U.S. Energy Information Administration's United States International Energy Outlook 2016 (IEO2016) reference case, global generation of electricity is projected to increase progressively from 2.2×10^{13} kWh in 2012 to 3.7×10^{13} kWh in 2040, making it the world's fastest-growing form of end-use energy consumption (see Fig. 1). To facilitate this, power systems are evolving from national to international infrastructures. While fossil fuels in general and coal in particular (declining from 40% of total world electricity generation in 2012 to 29% in 2040) is projected to continue to dominate, the adoption of national clean energy policies is nevertheless leading to significant investments in renewables in both developing and developed economies [2]. For example, in 2015, India dramatically increased its commitment to renewables by setting a target of 175 GW by 2022 [3], while the European Union's 2030 climate and energy framework aims to reduce greenhouse gas emission by 40%, relative to 1990 levels, exploit 27% share for renewable energy and improve energy efficiency by 27% by 2030 [4].

While the deployment of new, renewable sources of electricity generation is a clear target, such changes have major implications on transmission systems, such that the European Network of Transmission System Operators' Ten Year Network Development Plan envisages of the order of 150 billion euros of investments in grid infrastructure being required to support the transmission of large quantities of electricity from remote sites of generation to demand centres. The problem is well demonstrated in Germany, where low public acceptance of overhead power lines means that the Suedlink project will require the installation of a 700 km, 525 kV underground high-voltage direct current (HVDC) link from the northern seaboard to demand centres in the centre 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 of 12 GW [5]. While many HVDC subsea systems have been installed successfully, such underground systems on land pose many challenges, many of which relate to the choice of insulation system within the HVDC cable, particularly when system designers are considering HVDC transmission voltages of 800 kV to 1 MV to increase the transmission capacity of single circuits. This study sets out to describe an integrated approach to such problems; that is, an approach which combines a comprehensive consideration of the factors that need to be addressed to support the development of cable systems capable of operating at higher and higher voltages, together with potential material development strategies that can be adopted in order to render cable designs practicable.

Considering that the trend is towards longer length and higher voltages (to increase the specific power and reduce losses) three distinct aspects of the problem are addressed in the study, namely:

- Cable ratings and network operability.
- Cable design and constituent insulating materials requirements.
- Potential strategies for the design of novel insulation materials, where the required properties are actively 'designed in'.

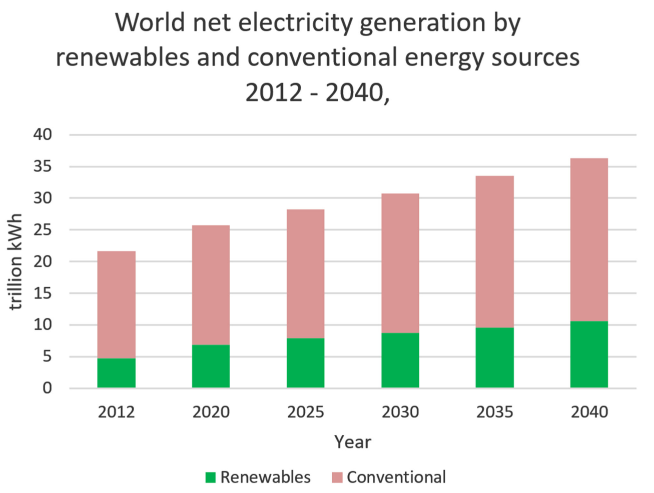

Fig. 1 *Projected growth in total global demand for electricity compared with the fraction produced using renewable sources. Source: [2]*

2 Insulation characteristics, cable rating, and network operation

A key parameter that relates to all cable installations is the cable rating, which depends upon numerous factors relating to both the design of the cable itself and its installation. Ultimately, the problem can be considered in terms of heat that is generated in the conductor being dissipated from the system such that excessive ageing does not occur – that is, thermal management becomes a challenge. Indeed, as system operating voltages increase, the requirement to limit the maximum electric field within the insulation will require the insulation thickness to increase, which exacerbates the problem of thermal runaway. Clearly, if an insulation system with improved breakdown characteristics was available such that operation under increased electric stress was acceptable, then this problem would be relieved, provided other pertinent material characteristics were not compromised. A major parameter determining the risk of thermal runaway is the field- and temperature-dependent insulation conductivity. The risk is the highest during the electrical type test at 1.85 times nominal operating voltage [6]. To reduce this risk, new insulation compounds are developed with a significantly reduced electrical conductivity to prevent thermal instability even at voltages above 600 kV [6]. Alternatively, thermal runaway can be avoided by increasing the thermal conductivity of the insulation compound. Summarising, a number of solutions to this problem have been proposed for cables and other high-voltage (HV) equipment of electrical power systems whereby some aspects of the insulation system being improved with respect to appropriate material parameters such as breakdown strength, permittivity and dielectric loss, electrical conductivity and thermal conductivity. Nevertheless, from the perspective of a network operator, major operational criteria are of much more importance. So, how much current can the cable carry, what is its overload rating capability and how does this influence the overall operational efficiency and flexibility of the system?

While HVDC and HV alternating current (HVAC) cables are somewhat different, the analysis of the latter case conducted by Pilgrim *et al.* [7] is, nevertheless, informative, with principles that address both cases. In this study, the impact of a number of pertinent insulation properties on two relevant operational parameters, namely the overall rating of the cable and the power losses incurred per unit power transmitted, were considered. In terms of the breakdown strength of the insulation, an increase was found to be beneficial in that in principle it can allow the insulation thickness to be reduced, thereby reducing the thermal resistance and hence increasing the cable's rating. However, in the case of an HVAC cable, this was also shown to lead to an increase in cable capacitance and, consequently, increased dielectric losses and a reduction in the maximum length of the cable circuit over which power could usefully be transferred. Evidently, changes in the real part of the relative permittivity of the insulation have an equivalent direct effect, while reductions in the dielectric loss were considered to be insignificant, given the low losses inherent in modern cable insulation materials. The final two parameters considered were related directly to thermal factors, namely thermal conductivity and the maximum acceptable operating temperature of the insulation, which will occur adjacent to the conductor. Improvements in both of these parameters will, in principle, reduce the thermal constraints placed on the cable and therefore increase the rating. The general methodology used in this analysis was to calculate a continuous rating using a modified form of IEC 60287 [8] for a three-phase 400 kV circuit based on three directly buried single core cables, each containing a 2500 mm^2 copper conductor.

The analysis considered the consequences of varying each of five insulation material parameters (breakdown strength; the real part of the relative permittivity; the dielectric loss; maximum operating temperature; thermal conductivity) and evaluated the impact of changing each over three levels. This led to a number of significant conclusions. First, in the HVAC case, the most significant improvement in overall operational performance was found to result from an increase in the thermal conductivity of the insulation; indeed, a sensitivity analysis showed that this was still beneficial even if it were accompanied by a small reduction in breakdown strength, which could be counteracted by an increase in the thickness of the dielectric. Conversely, increasing the dielectric loss was found to have deleterious consequences. Increasing the operating temperature was shown also to be capable of leading to increased ratings, albeit that this resulted in increased overall losses. The acceptability of this, or otherwise, will depend upon the cable installation and operational scenarios, the economic consequences of achieving higher rating versus incurring increased system losses, and the acceptability of other factors that may be set by network or regulator policies. Hence, the need to consider the wider picture and multiple operational factors.

Elsewhere [9], a complementary methodology was used to consider the effect of insulation material type and parameters on both the steady state and transient responses of an HVAC cable (400 kV; copper conductor of 2500 mm^2 in cross-sectional area) as part of a power system. In this case, a range of different cable deployment scenarios have been simulated but, for the sake of brevity, only the case of directly buried cables is reported here. By adopting a coupled multi-physics, finite element approach, it was shown that under steady state conditions, a dielectric capable of sustaining continuous operation at 150°C, could lead to a continuous rating that was increased by more than 30% compared with a current cross-linked polyethylene (XLPE) insulated design. Prolonged operation at such a high temperature was shown to result in significant migration of water within the soil and drying of the ground surface, effects that were deemed undesirable. However, transient response analysis based on preload conditions commensurate with current practice for XLPE-insulated cables indicated that for a cable insulated with a dielectric able safely to withstand continuous operation at just 120°C (cf. 90°C for XLPE), emergency ratings could be extended from 6 h, at present, to 24 h. Thus, we conclude that optimisation of the material system used within an HVAC cable system, be it through improved heat dissipation or through increased operational temperature, are able to offer significant network operational benefits. Similar thinking can be applied to HVDC cables. Since material factors influence cable performance and, thereby, network operation, these factors need to be addressed in concert if the optimal performance of the whole system is to be achieved.

3 HVDC cable design methodologies

The design of HVDC cables and the choice of the constituent material systems must reflect the general issues raised above. For example, where an HVDC system is used to connect intermittent renewables to centres of demand, power flows are likely to fluctuate significantly and, in such circumstances, the ability to accommodate this through the use of an insulation system that is able to withstand an intermittent high operating temperature may be economically attractive, despite the increased losses during the intermittent use that is a necessary corollary of this strategy.

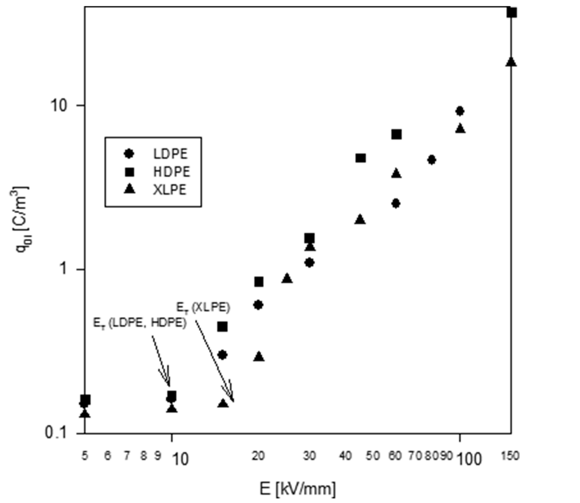

Fig. 2 *Threshold characteristic of space charge for LDPE, XLPE and HDPE specimens (the threshold is indicated by arrows). After [12]*

However, the design of an HVDC cable system poses particular problems that go above and beyond the general issues outlined above.

Recently, Feng *et al.* [10] reported a study into the effect of material factors on the design of medium voltage direct current (DC) cables for use in applications where high power densities were required – marine applications being mentioned as an area where such characteristics would be beneficial. Although the study focuses on a highly unusual base polymer where the 'glass transition temperature is 350°C', which would appear to render the material system inapplicable for use in cable applications, the essence of the work revolves around the implications for DC cable design of a significant increase in thermal conductivity which, in the example cited, can be attributed to the enhanced thermal conductivity brought about by the inclusion of appropriately exfoliated hexagonal boron nitride [11]. While the veracity of certain aspects of the analysis could be disputed, the importance placed on space charge accumulation and the broad conclusion that material factors critically determine cable performance and that by optimising pertinent parameters, enhanced cable designs can be developed which are optimised with respect to the envisaged application area are important points.

We have recently adopted a complementary approach to the optimisation of HVDC cable geometries which specifically focuses on the challenges associated with driving such systems to HVs and high current (ampacity). The design of an ultra-HVDC (UHVDC) cable would require very high short-term breakdown strength and long-term voltage endurance aging coefficient (obtained from the inverse of the life line slope in log-log plot), together with a very low dispersion in electrical breakdown properties (in both time and field domains). While these requisites are comparable to those demanded by the HVAC case, under HVDC conditions, the physics that defines the electric field distribution involves conductivity (rather than permittivity and capacitance). This means that the activation energy of the conduction process, which is strongly temperature dependent [12], will play a fundamental role in determining the field profile as a function of cable radius in the presence of a temperature gradient within the insulation, which can become significant if the cable ampacity becomes high.

An additional factor that will further influence the electric field distribution within the insulation is the threshold for space charge accumulation. If the cable has to operate with the design reliability, the maximum electrical field within the insulation must be lower (*at the operating temperature*) than the threshold for space charge accumulation [12–15]; see also Fig. 2. Lan *et al.* [16] examined the effect of temperature on both space charge trapping and conduction in XLPE. In this study, the threshold field for heterocharge accumulation was reported to decrease from 20 kV/mm at 30°C to <10 kV/mm at 90°C; a similar reduction in the threshold field for homocharge accumulation was also reported, albeit that the reported numerical electric field values were significantly higher (50 kV/mm at 30°C and 20 kV/mm at 90°C). While these results provide useful indicators of the electric fields at which space charge effects could be anticipated, the precise numerical values will be dependent on numerous factors. Indeed, it has been experimentally shown that the space charge threshold is dependent on both cross-linking by-products and on material factors, since significant differences were seen between different XLPE systems, even when factors related to dicumyl peroxide (DCP) cross-linking residues were set aside [17]. Therefore, the capability of the insulating material to generate and store space charge under a range of high field, thermal and aged conditions will be a fundamental requirement for the development of UHVDC cables.

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 favoured. In this case, even more so, the control of the activation energy of the conduction process is an imperative (in order to reduce the variation of conductivity as a function of thermal gradient in the dielectric and, thus the maximum field value), and will be important for the selection of insulating polymer candidates for UHVDC applications.

In summary, the combination of HV and high current may render cable feasibility critical considering the material used at present for HVAC and HVDC cables which are mostly XLPE. This supports the efforts started recently in investigating polymeric materials and/or nanostructured materials different from XLPE such as thermoplastic materials and associated nanocomposites.

4 Active material design for next-generation HVDC cables

XLPE has been a mainstay of alternating current (AC) cable manufacture for many decades and, in recent times, its impact on HVDC cable technology has been growing as demonstrated, for example, by NKT's launch of a 640 kV XLPE-based HVDC cable design capable of transmitting at least 3 GW [18]. While this product is cited as exploiting 'a new DC cross-linked polyethylene (XLPE) insulation material developed with Borealis', the limitations inherent in the use of crosslinking as a means of improving the thermo-mechanical performance of low density polyethylene (LDPE) to enable the continuous operating temperature of 90°C, remain. While this applies to both AC and DC conditions, the importance placed upon space charge accumulation under HVDC conditions poses other problems for XLPE.

The cross-linking reaction of LDPE with DCP has been studied for many years [19] and the presence of retained cross-linking by-products has been shown adversely to affect space charge accumulation. For example, Hirai *et al.* [20] reported on experimental studies of the effect of a number of the key products of DCP decomposition on charge transport and trapping in polyethylene, concluding that while acetophenone and α-methylstyrene assisted carrier transport, cumylalcohol acted as a trap for charge carriers. Elsewhere, Meunier *et al.*[21] examined the same issues theoretically, by using density-functional theory to evaluate electron trap depths associated with 13 impurities and decomposition products; this work indicated that the trap depths associated with acetophenone, α-methylstyrene and cumylalcohol are 0.90, 1.53, and 0.28 eV, respectively. Since the residence time of electrons in traps would be expected to increase approximately exponentially with trap depth, Meunier *et al.* [21] concluded that, at least as far as electron trapping is concerned, it is the deep chemical traps that lead to long lived space charge which, as far as the three compounds considered above are concerned, would suggest that acetophenone and α-methylstyrene should be most strongly related to trapping phenomena, which is in marked contrast to the conclusions of Hirai *et al.* [20]. Nevertheless, despite their differences, both experimental and theoretical approaches indicate that the by-products generated through the decomposition of DCP affect space charge formation in polyethylene, which in turn will increase the local field and thereby reduce service life. As such, a number of different strategies have been proposed to modify appropriate parameters, such as

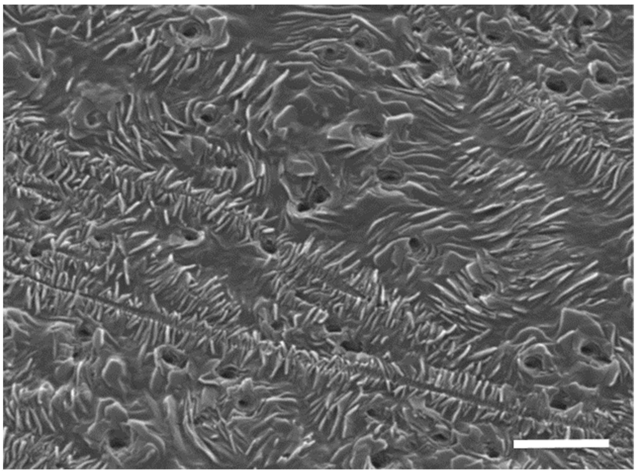

Fig. 3 *Scanning electron micrograph showing the morphology of a blend containing 20% HDPE, 80% LDPE plus 1 part DBS per 100 parts polymer. The DBS exists as elongated fibrils which both nucleate the polymer matrix and directly influence charge transport dynamics (scale bar: 2 μm)*

breakdown strength, electrical conductivity, space charge accumulation, thermal performance, etc., in order to generate materials that are specifically optimised to meet the requirements of particular applications.

4.1 Nanodielectrics

Since the potential implications of including nanofillers were first proposed by Lewis [22] in 1994, the concept has generated massive global interest as a potential means of producing insulation material systems with enhanced combinations of properties. However, while the potential of the approach is clear, widespread technological adoption has been hampered by issues related to reproducibility, scale up and a general lack of understanding of the underlying mechanisms and how these can be actively controlled. Although the effect of adding nanoparticles on pertinent electrical, mechanical and thermal parameters has been considered, by way of illustration, we will consider just the DC breakdown strength. As described above, the development of UHVDC cables will require the availability of insulation systems that exhibit very high short-term breakdown strength.

Roy *et al.* [23, 24] reported on the effect of adding 5% of silica (SiO_2) to cross-linked polyethylene (XLPE), which showed that while the inclusion of 5% of the micron-sized filler markedly reduced the DC breakdown strength and the addition of 5% of untreated nanofiller gave a level of performance that was comparable to that of unfilled XLPE, it was found that appropriately surface modified silica increased the breakdown strength. Elsewhere, Murakami *et al.* [25] examined DC breakdown in systems based upon LDPE containing nano-metric magnesium oxide (MgO) and reported an increase in DC breakdown strength approaching 50% on adding just 2% of this nanofiller. In the case of polypropylene (PP) [26], an increase in DC breakdown strength from 511–778 kV/mm was seen by adding 5% of hydrophobic fumed silica.

While the above examples all indicate that adding nanoparticles can lead to an improvement in DC performance, this conclusion is far from universal. Hong *et al.* [27] considered a range of different systems based upon zinc oxide (ZnO) and LDPE, reporting a monotonic decrease in strength with increasing filler loading both for micro-metric and nano-metric ZnO. Elsewhere, [28] a reduction in DC breakdown strength approaching 40% was reported on adding nano-metric titania (TiO_2) nanoparticles to LDPE, albeit that this situation could be improved by thoroughly drying the nanofiller. Detailed studies of the effect of nanoparticle surface chemistry and absorbed water have shown that while such factors dramatically influence DC breakdown behaviour in systems based upon nanosilica and blends of low and high density polyethylene (HDPE), in none of the systems considered was enhanced DC breakdown strength seen [29, 30].

4.2 Molecular additives

The difference in behaviour between composite subsystem based on the same loading level of micro-metric and nano-metric fillers, suggests that control of the agglomeration state of nanofillers is key in controlling the macroscopic properties of nanocomposites. The same explanation has been proposed to account for the reported trend, in which the addition of a nanofiller initially enhances performance but, beyond a certain loading level, agglomeration effects begin to dominate, thereby leading to inferior performance to that observed at lower nanofiller loading levels, or indeed, in the unfilled polymer [31]. In the case of non-polar polymers such as polyethylene and hydrophilic nanofillers such as the metal oxides discussed above, achieving thermodynamic compatibility is inherently difficult and, for this reason, alternative strategies that are not prone to dispersion issues could be attractive.

An interesting approach that built upon a great deal of solid fundamental study [32–34] has recently been reported, in which a very small quantity of HDPE was added to LDPE and then cross-linked using a standard DCP process [35]. In this work, it was suggested that electrical conductivity constitutes a limiting parameter where HVDC insulation systems are concerned and showed that by adding as little as 1 wt% of HDPE, as a polymer additive, a reduction in the conductivity of about an order of magnitude could result. It was further proposed that this effect could be explained by the formation of an array of relatively thick lamellar crystals that are dispersed throughout the system. The phenomenon, whereby the addition of a very small fraction of a linear polymer can exert an apparently unduly large effect on the overall morphology of the system, was first reported by Puig and explained, morphologically, in terms of the HDPE fraction co-crystallising with the more linear molecular segments within the majority LDPE component [36].

Many small molecular additives have been incorporated into polymers to modify particular aspects of behaviour. In terms of electrical parameters, so-called voltage stabilisers have long been studied, but an alternative approach first reported in 2001, has attracted recent attention as a consequence of its potential as a means of suppressing charge trapping. Sorbitols constitute a versatile family of small molecules that find applications ranging from food additives to polymer clarifiers for use in packaging systems. Li *et al.* [37] reported on the effect of adding bis-(*p*-ethyl-benzylidene)sorbitol to a cable grade LDPE and showed that the inclusion of just 0.3% of this additive resulted in reduced space charge accumulation and an increased rate of space charge decay compared with the LDPE alone. This effect was explained by the nucleating effect of dibenzylided sorbitol (DBS) which, it was suggested, prevents the accumulation of impurities and defects at interspherulitic boundaries. In more recent work, this mechanistic hypothesis was questioned since in blend systems composed of HDPE and LDPE, where impurity segregation is suppressed, the beneficial effects of adding DBS were found to be restricted to concentrations around 0.3%, with space charge decay occurring more slowly in systems containing higher concentrations of DBS (1 and 3% in this work) [38]. This suggests that nucleation and impurity effects are less important than the nature of the DBS gel phase, which appears in Fig. 3 as elongated channels, due to the sample preparation technique used to reveal the morphology of the system prior to examination in the scanning electron microscope. In 2013, ABB filed the patent WO2014206437, '*A New Process for Preparing Insulation Materials for High Voltage Power Applications and New Insulation Materials*' [39] which sought to exploit DBS, albeit that the patent focused on processability, rather than the properties of the ultimate material system.

4.3 Self-assembly

While XLPE undoubtedly holds a dominant position in the extruded cable insulation sphere, a radically different approach has been evolving over recent years, culminating in late 2016 with the announcement by Prysmian of a 600 kV HVDC P-Laser cable system, where the insulation is based upon 'in-house developed thermoplastic material – known as HPTE (High Performance

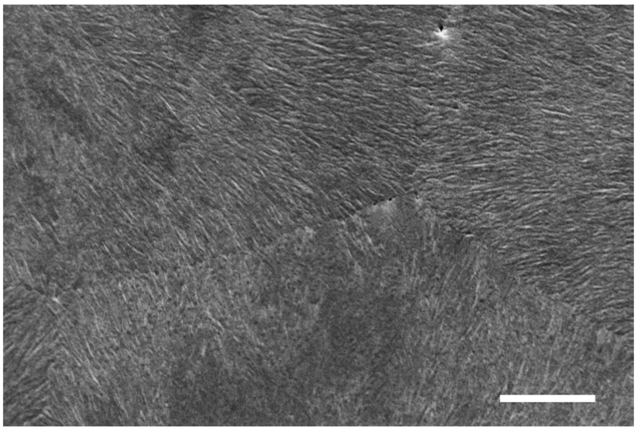

Fig. 4 *Scanning electron micrograph showing the morphology of a propylene-based blend containing 50% iPP and 50% of a low crystallinity ethylene/propylene copolymer after isothermal crystallised at 120°C; where a copolymer was chose such that phase separation issues do not occur (scale bar: 20 µm)*

Thermoplastic Elastomer)' [40]. The generic advantages of the use of thermoplastic insulation, rather than a cross-linked system are cited as including [41]:

- Operating temperature range increased to 130°C, thereby delivering increased network operational flexibility and reduced risk of financial penalties.
- Increased production efficiency leading to superior service due to no requirement to degas the system to remove DCP cross-linking residues.
- Reduced whole life environmental impact stemming from increased energy efficiency and reduced greenhouse gas emissions during manufacture and ease of recycling of the insulation at the end of the cable's service life.

From the HVDC perspective, the importance placed upon reduced impurity levels and the potential for improved space charge performance that this brings, would appear to make thermoplastics particularly suitable technologically, while Prysmian's claim that their 'New P-Laser 600 kV HVDC System allows a cost reduction of up to 30% per transmitted MW' [40] is economically attractive.

The interest in using thermoplastic polymers as insulation systems is evident from the patent literature, with representative examples including those filed by Dow Global Technologies Inc. (WO 2007019088 A1, '*Polypropylene-based wire and cable insulation or jacket*', published February 2007) [42] and Borealis Technology Oy (WO 2009077444 A1, '*Cable layer of modified soft polypropylene*', published June 2009) [43]. However, a key feature of such systems is their morphological complexity [44] and consequently, since the presence of complex hierarchical microstructures can lead to electrically weak regions [45], practical design of thermoplastic insulation systems that truly manifest the potential promise is far from straightforward.

The nature of the challenge is well illustrated in a number of papers published by Hosier *et al.* [46, 47], which illustrate the fundamental principles involved with reference to blends of HDPE and LDPE. This work showed that, for such a two-component system, if crystallisation of the HDPE into a space-filling array of lamellar crystals can be made to occur at a temperature where the LDPE remains in the liquid phase, then the mechanisms that, elsewhere [45], lead to electrical weakness can be suppressed. The resulting material can then exhibit increased breakdown strength, good low temperature flexibility (from the soft, disperse LDPE phase) and high temperature mechanical integrity (from the high melting 'skeleton' of thick HDPE crystals). Extending these ideas to the high temperature melting polymer PP is, however, far from trivial. A scanning electron micrograph of the morphology of a propylene based blend is shown in Fig. 4. Although the high melting homopolymer isotactic PP (iPP) and an appropriate lower melting propylene-based copolymer can be used as analogues of HDPE and LDPE, respectively, suppressing the processes that lead to electrical weakness is, practically, far more complex in PP blends than it is in polyethylene blends. Nevertheless, two of us have shown that it is possible to design propylene-based materials that exhibit excellent combinations of mechanical and electrical properties, that these can be extruded into cable geometries and that the resultant prototype mini-cables retain the desirable characteristics of the laboratory-produce plaque materials [48]. Indeed, during a progressive stress test, none of the PP-insulated mini-cable specimens failed up to an applied DC voltage of 400 kV. This corresponds to a maximum electric field within the insulation in excess of 120 kV/mm. In contrast, all the XLPE-insulated mini-cables failed at applied DC voltages between 168 and 224 kV, despite being manufactured with an insulation that was found to be nearly 30% thicker than for the PP-insulated mini-cables [48].

5 Conclusions

The power systems of the future will be radically different from the traditional, national AC systems that have dominated thus far. The need to exploit remote renewable generation resources and the benefits that stem from the interconnection of national power systems to produce new super-grids will force an increasing reliance on HVDC and UHVDC systems. While many elements that will contribute to this revolution are already in place, others are not, and the development of cable systems that are capable of being integrated into UHVDC systems at the voltage levels that are currently being used with overhead lines represents a major technological problem. While, traditionally, HV and ultra-HV cable technologies have evolved through the refinement of systems initially proven at lower voltages, the coupling of electrical (breakdown, conduction, and space charge) and thermal (conductivity and maximum operating temperature) issues that will control UHVDC cables of high ampacity suggests that a more integrated approach is required. This approach must be able to link material characteristics and cable design to anticipated network operational requirements with the limits and challenges of insulating materials design and manufacturing. A number of complementary strategies for the development of novel material technologies are emerging but, for these to be fully exploited, novel UHVDC cable design approaches are required that recognise and incorporate the underlying physical and chemical mechanisms that determine service performance and ultimate service lifetimes. It can be argued that the existing approaches, based on conventional materials already used in HVAC may provide a bridge to potential solutions, which address specifically the needs of HVDC cables in the light of the integrated approach introduced in this study. However, it is likely that new materials will be required to meet these challenges. Indeed, the recent development of refined XLPE-based insulation systems, which have been developed specifically to suppress the causes of space charge, represents an initial step along this route. As described here, a number of more radical material strategies are also emerging, but it is not clear which of these will find market acceptance as this depends upon the value placed on the potential network operational benefits that result, balanced against the perceived risks of using a new materials technology.

6 Acknowledgments

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