Next generation polymeric HVDC cables – a quantum leap needed?

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This article describes the main problems associated with, and potential strategies for, the design and manufacture of next-generation HVDC cable systems, with a focus on increasing power flows over long distances.

Introduction

The attention given to high voltage direct current (HVDC) cables appears to be at an all-time high. In the July/August 2017 issue of the Electrical Insulation Magazine, the focus was on different aspects of the design and testing of HVDC cable systems. There are several reasons for this, one of the most important probably being the world wide attention for harvesting renewable energy at a scale never seen before. The prices of building large offshore windfarms in Europe as reflected in a recent normalized cost of electricity have unexpectedly dropped in the last year, as illustrated in Figure 1, which will further accelerate the development of HVDC cables to link offshore and onshore substations. The winning bid in 2016 for the Borssele II, 700 MW windfarm in the Netherlands was as low as 54.5 € ($US 61)/MWh) [1].

Perhaps the strongest drivers now are the developments of high power HVDC corridors on land in Germany and China. In Germany, a large amount of offshore wind generation needs to be integrated into the grid, requiring a 525 kV corridor from North to South (Südlink). A very substantial part of this corridor will be realized with underground HVDC links because of the low public acceptance of overhead power lines. 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 [3]. While many HVDC subsea systems have been installed successfully, such underground systems on land pose considerable challenges, many of which relate to the choice of insulation system within the HVDC cable. In China, the developments in the field of HVDC are further speeding up. In 2016, there are some 22 HVDC transmission systems commissioned or in operation, including the +-800kV Shanghaimiao-Shandong HVDC project with a planned transmission capacity of 10 GW [4]. In May 2017, the Chinese president Xi Jinping announced further details about the One Belt One Road policy, including energy corridors connecting China and Europe [4]. In addition, strategic projects are being planned to interconnect Asian countries, see Figure 2.

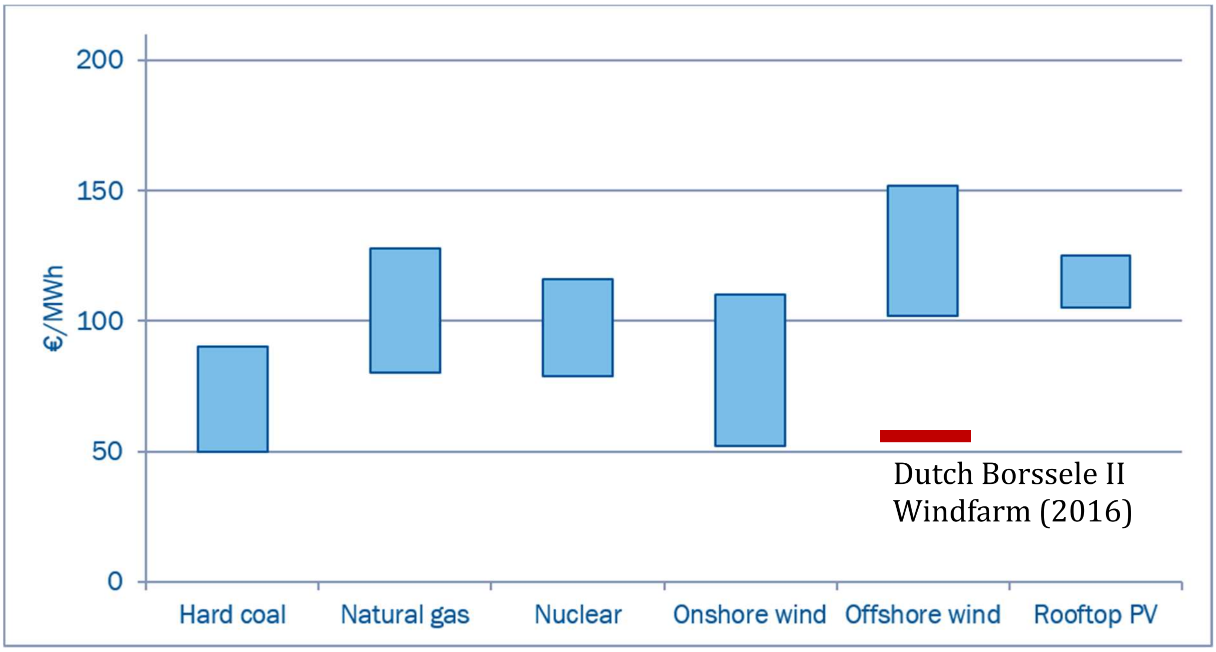

Figure 1 – Normalized cost of electricity in Europe for different energy carriers, end of 2014, Source: [2]. The cost of offshore wind has plummeted, as exemplified by the 54.5€($US 61)/MWh bid for the Dutch Borssele II windfarm, in 2016 [1].

The decisions to transport electrical energy over very long distances will naturally lead to increasing voltage levels. A substantial part of the HVDC corridors will have to be installed underground, using HVDC cable technology. While major cable and cable insulation manufacturers are developing polymeric HVDC cables for higher and higher operating voltage (640 kV XLPE, 700 kV MI-PPL), the question remains how far we can go with pushing the current technologies to even higher voltage levels.

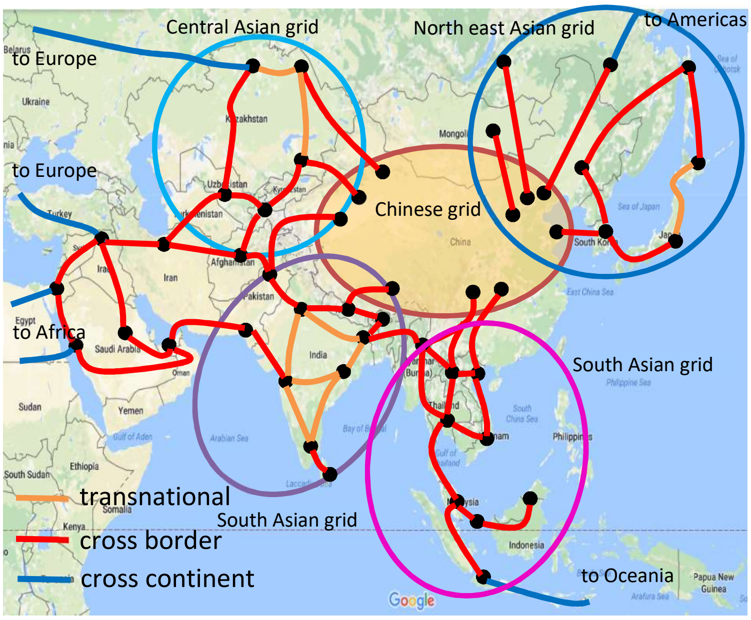

Figure 2 - Long distance connections in Asia proposed by [6].

This article describes the main problems associated with, and potential strategies for, the design and manufacture of next-generation HVDC cable systems, with a focus on increasing power flows over long distances. First, using an electrical-statistical design procedure combined with a thermal design procedure, the feasibility of using XLPE insulation for 800 kV cable systems is analyzed for a number of material design parameters. Following the case study, the options of using XLPE are discussed. A preliminary conclusion is that the use of XLPE may not be feasible and the rationale for this in terms of material performance gaps is discussed. Then, some potential material strategies are discussed to address these material performance gaps and tackle the challenges in designing reliable cable systems for HVDC voltages for the next decades. The development of proper cable accessories for such systems is a very challenging topic that deserves considerable attention but it is out of the scope of this paper.

HVDC Cable Feasibility and Simulation

To obtain an idea of which cable insulation parameters determine a successful design of HVDC polymeric cables, simulations were made for an XLPE based cable assuming a potential wide range of parameter values. The simulation approach is based on a combination of an electrical-statistical design and a thermal design. A detailed description of the model goes beyond the scope of this article and will be published elsewhere.

The design is divided into two interacting steps:

a) Electrical-statistical design, which aims to define the insulation geometry that is necessary to ensure the electrical performance;

b) Thermal design, which aims to verify that the maximum temperature inside the insulation does not lead to overheating (and thus to a life reduction through the Arrhenius law) or even thermal runaway.

A strong coupling exists between the electrical and thermal design through the temperature dependence of the insulation resistivity. For all simulations it is assumed that the cable is operated below the threshold for space charge accumulation, i.e. the cable is space charge free, except for the charge distribution that is the result of a temperature gradient in the insulation. If space charge would be included it would definitely have a negative effect on the lifetime of the cable.

Electrical-statistical design

For the electrical-statistical design, it is assumed that the life line correlating the electric stress and the time to failure for a given failure probability, using the inverse power law model (IPM) is available through testing in the laboratory, for a particular insulating material or insulation system of a fixed geometry [7]. Assuming that L_d is the design life for the cable insulation (typically L_d = 30 years), the IPM model allows the electric field E_1 able to ensure life L_d at p_t percentile to be calculated, with n the voltage endurance coefficient:

$$E_1 = E_0(\frac{L_d}{L_0})^{-\frac{1}{n}}. \qquad (1)$$

Usually, E_0 is chosen equal to ES_0, i.e. the dielectric strength of the material (at constant time) and L_0 is therefore the time at which breakdown occurs (p_t percentile). The dimensional effect, using the real cable geometry, can be taken into account by considering the following expression [8], which allows the electric field, E_2, providing life L_d to the real cable insulation, to be obtained at probability p_t:

$$E_2 = E_1\left[\frac{l_t}{l_d}\left(\frac{R_{it}}{R_{id}}\right)^2\left(\frac{1-\left(\frac{R_{it}}{R_{ot}}\right)^{\beta_e-2}}{1-\left(\frac{R_{id}}{R_{od}}\right)^{\beta_e-2}}\right)\right]^{\frac{1}{\beta_e}} \qquad (2)$$

where the subscript t refers to the test sample and the subscript d to the cable insulation. Table 1 summarizes the meaning of the parameters used in (2).

Table 1: List of the parameters used in (2).

Parameter	Meaning
$l_{t,d}$	Lengths of tested and real cables
$R_{ot,d}$	External radius of tested and real cables
$R_{it,d}$	Internal radius of tested and real cables
β_e	Weibull shape parameter of dielectric strength tests

The cable external radius, R_o, is assumed to be equal to the extruder radius, R, for the insulation material, and for this reason, in the following, $E_2 = E_2(R_{id})$. Finally, the electric field E_3, leading to a cable insulation life L_d with failure probability p_d, can be estimated in the following way:

$$E_3 = E_2 \left(\frac{\log(1 - p_d)}{\log(1 - p_t)} \right)^{\frac{1}{N\beta_t}} \qquad (3)$$

where β_t represents the Weibull shape parameter fitting to the life tests performed on the investigated samples, and $N = l_d/l_t$. Due to the presence of E_2 in (3), the field E_3 is not directly known, but it depends on the internal radius of the cable insulation, i.e. E_3=$E_3(R_{id})$. A feasible solution for the design is found if the electric field E_3 is equal to or higher than the maximum electrical field inside the cable insulation E_{max}, in order to guarantee the desired cable lifetime at the desired reliability. In order to determine the electric field distribution, it is assumed that the insulation conductivity has an exponential dependence upon temperature.

$$\sigma = \sigma_0 e^{\alpha T} \qquad (4)$$

where σ_0 represents the conductivity at 0 °C, T the temperature, and α the temperature coefficient [9].

Thermal design

The aim of the thermal design is to verify if the temperature distribution inside the previously electrically-designed cable is acceptable with the ampacity that is required for the intended use of the cable. It is assumed that the only heat source is represented by the Joule losses of the internal conductor, $R_{cc}I^2$, neglecting the insulation losses. It is reasoned that with the latest XLPE compounds to be used for HVDC cables the insulation losses are minimized to the extent that thermal instability is highly unlikely. We assume that the temperature distribution is acceptable when, considering an earth temperature of 25° C, the total temperature drop is lower than 65° C, i.e. the maximum temperature inside the cable is 90° C (direct buried XLPE cable).

Simulation results

Table 2 shows the initial parameters which have been selected for the simulations, and are considered typical for a high-voltage grade XLPE. The voltage U and the maximum continuous load current I_n were chosen as 800 kV and 3750 A. In order to investigate feasibility, as well as understand the effect of the insulating material parameters on feasibility, several simulations were undertaken where the chosen values of key parameters were varied, as indicated in Table 3. This allows an investigation of the effect of each (or a combination of) parameter on the cable feasibility, thus supporting the future selection and design of new materials for HVDC applications, if and when needed.

Table 2: Initial simulation parameter values for XLPE insulated cable.

Parameter [unit]	Value
t_0 [h]	5e-4
p_t [%]	50
R_{it} [m]	2e-3
R_{ot} [m]	3e-3
l_t [m]	1
L_d [y]	30
p_d [%]	0.01
U [kV]	800

Table 3: Insulation parameter variation range for the simulations. The values indicated in red are used as constant parameters in Figure 3.

Parameter [unit]	Value
n	10-12-15-20
ES_0 [kV/mm]	250-300-375-500
α [°C^{-1}]	0.05-0.1-0.12-0.15
β_e	12-20-30-50
β_t	1-2-3-5
l_d [km]	1-10-100-1000
I_n [kA]	0.5-1.5-3-3.75

To summarize the simulation results and to obtain a first impression of the sensitivity of the design to each insulation parameter (i.e. their influence on E_3 and E_{max}), contour plots showing the behavior of the maximum electric field E_{max} and of the design field E_3, for various values of the major insulation parameters are shown in Figure 3. The simulations show that for all parameter values, there is no feasible design, i.e. E_{max} is always larger than E_3. As these parameter values were taken from typical XLPE data, we may conclude that it is unlikely that an 800 kV HVDC cable with practical values for the maximum continuous load current can be designed using the currently existing XLPE insulation compounds.

The behavior under transient conditions and situations with a maximum thermal gradient such as when the cable is energized may lead to the maximum field changing relative to the steady state condition. These situations will require further simulation work to understand any additional risks beyond those identified for the worst steady state conditions at maximum load and largest thermal gradient. Some additional modeling work may be beneficial for a range of operating conditions that could be anticipated from system modelling.

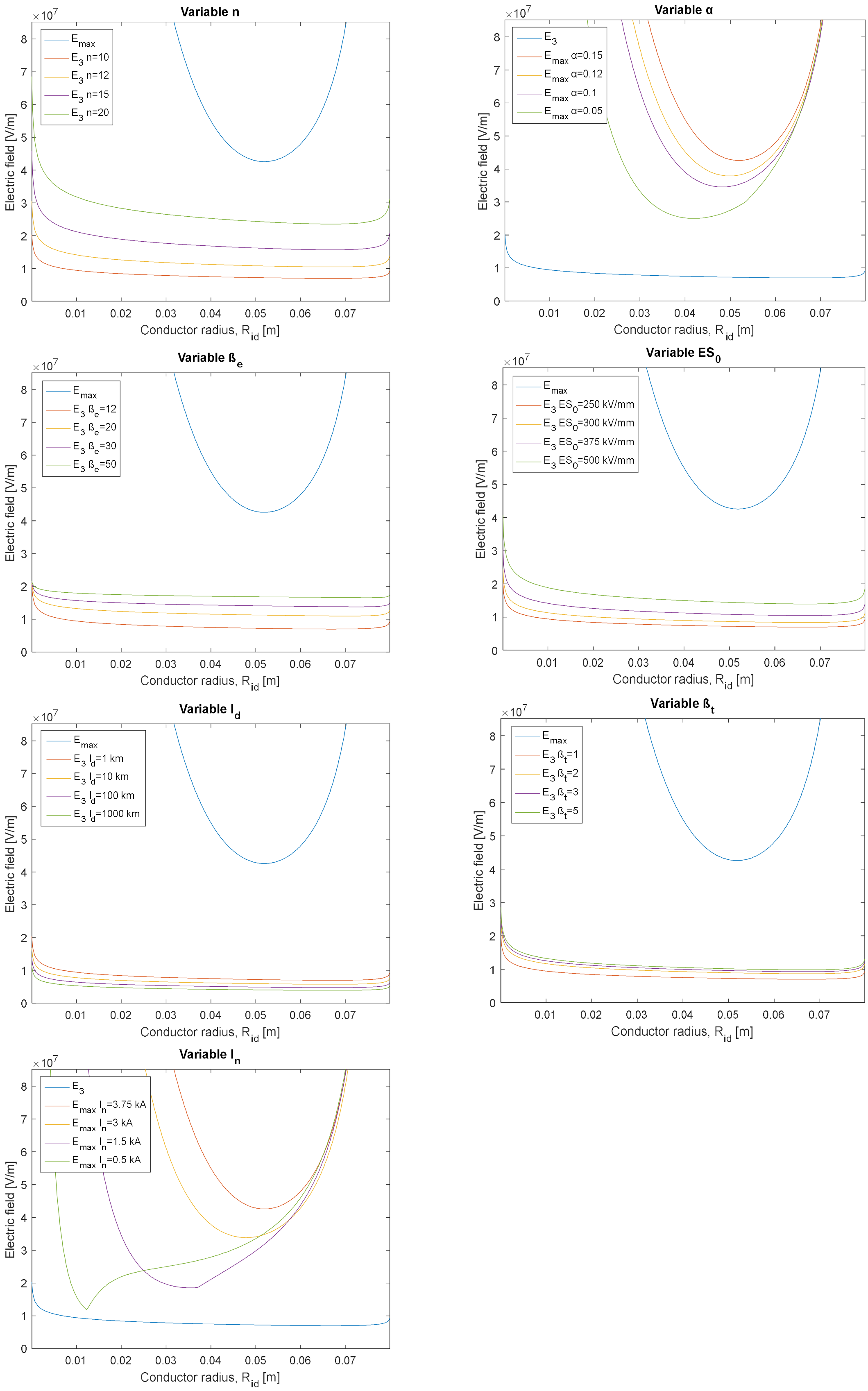

Figure 3 - Contour plots for E_{max} and E_3 for different values of key insulation parameters n, α, β_e, ES_0, l_d, β_t, and I_n. The values of the constant parameters are indicated in red in Table 3.

Material Performance Gaps

Based on the results of the simulations, it is clear that the feasibility of a 800 kV DC cable, with a high steady-state ampacity, is questionable considering the technologies and the characteristics and properties of the insulation materials most commonly used in extruded polymeric cables, XLPE in particular.

There is a need for a very high breakdown strength and a large value of the voltage endurance coefficient (VEC – the inverse of the life line slope), also in relation to the dimensional effect, (2). In order to increase cable length, a major issue is the value of the shape parameter of the Weibull distribution of breakdown strength β_e and failure times β_t that must be as high as possible, which reflects the need to have maximum homogeneity of the insulation, placing demands on both the material and the extrusion process.

The extruder for an 800 kV 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. In this regard, the activation energy of the conduction process in the insulation (proportional to α) has to be lowered as much as possible, to reduce the dependence of the conductivity on the temperature gradient (thus on cable ampacity).

The above is summarized in Figure 3, where it can be seen that using parameters that are near to those characteristic of HVDC grade XLPE, and even allowing a significant variation in them, no feasible solution is possible. The only chance could be to reduce significantly the current rating, or allow the current density to go to values so low that the electrical design feasibility will not match the system target and economic criteria.

Also the space charge accumulation threshold will become an issue, because if the cable has to run with the 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 HVDC cables. This may introduce the need to investigate nanostructured materials and/or polymeric materials different from XLPE (such as thermoplastic materials), and, also to increase the maximum operating temperature and related thermal classification. In addition, if the operating temperature can be raised above the present limit established by the thermal characteristics of XLPE, i.e. 90 °C, the increase of ampacity will be favored. In this case, even more, the control of 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 important for the insulating polymer candidates chosen for HVDC applications. This can only be achieved through the development of new materials some of which are currently emerging.

Potential Material Strategies

The most significant parameters which could be varied to achieve the success of the electrical design are the nominal current I_n, the VEC, n, the dc conductivity σ_0 at 0 °C and its temperature coefficient, α, and the Weibull shape parameter β_e. Based on the results shown above, other simulations were undertaken where the combination of insulation parameters was varied well beyond the data set in Table 2. From this, it has been shown that it is possible to achieve a feasible design of the proposed cable in a number of ways. An example of one such combination of properties is shown in Table 4.

The types of material that may present an appropriate combination of insulation parameters include:

- high purity uncrosslinked polymer blends,
- high thermal stability thermoplastic systems,
- use of the same polymer matrices containing structural control via the polymer nanophase or of nanophase additions that not only provide the electrical and thermal performance requirements but also achieve a balance of properties and processibility that enable HV cable to be produced and to operate.

Table 4. Combination of insulation parameter values bringing to cable feasibility.

Parameter [unit]	Value
N	18
ES_0 [kV/mm]	250
α [°C^{-1}]	0.05
β_e	40
β_t	2
l_d [km]	1
I_n [kA]	3.75

The space charge accumulation threshold will become an issue in achieving useful cable lifetime and reliability. As commented, the maximum electrical field must be lower than the threshold for space charge accumulation [10], [11], to avoid excessive charge build up at high fields and at semiconductor screen interfaces. This will introduce the opportunity to utilize novel polymeric and nanostructured materials different from XLPE and a number of new emerging thermoplastic blend materials in combination with defined functionalized nanofillers are showing great promise in achieving this. Their high chemical purity in comparison with XLPE systems also provides dielectric and electrical properties that favor HVDC.

Such thermoplastic composite materials will also favor an increase of the maximum operating temperature and related thermal classification, although care will need to be exercised in regard to conductor losses at elevated operational temperatures and the related semiconductor screen and sheath performance to enable such operating temperatures to be sustained. For example, in one combination of insulation properties in a nominal 800 kV DC design, in going from 90 to 120 °C the conductor radius dropped from 41 to 36 mm. If the operating temperature can be raised above the present limit established by the thermal characteristics of XLPE, i.e. 90 °C, a significant increase in ampacity can be achieved, albeit with increased conductor losses.

In this case, the control of the activation energy of the conduction process will become important for the insulating polymer candidates chosen for HVDC applications. This can be achieved through the development of new materials in which the matrix has intrinsic low conductivity and where this may be further reduced and the temperature activation energy increased by the addition of functionalized nano fillers and control of the carrier trap distribution to achieve this – a number of materials are emerging which support this.

It is important to consider other factors that may also contribute to a strategy for success. There is a need for a very high breakdown strength and large value of VEC, but these values must be maintained in relation to the cable length as dimensional affects are a major issue. The same is true for the value of the shape parameter of the Weibull distribution of breakdown strength and failure times; this must be as high as possible, which reflects the need to have very high homogeneity of the insulation system, placing demands on both the quality and uniformity of the material and the extrusion process and the means efficiently to assess if adequate homogeneity has been achieved.

Conclusions

It is unlikely that HVDC cables using the current XLPE compounds are feasible, at least at the voltage and power level which may be required in the near future. For a successful development of HVDC cables, there are several outstanding research questions to be tackled, which relate to the cable design, the further development of insulation materials, and the lifetime of the insulation systems to be used in 800 kV HVDC networks. These include:

1. Understand if existing thermoplastic materials available at either medium voltage DC or HVDC can satisfy the design criteria.

2. Define and further develop nanostructured thermoplastic material designs that could overcome the limitations of existing XLPE materials and simplify the manufacturing requirements for HVDC cable designs.

3. Ensure semicon materials development is linked to the actual insulation materials development to satisfy the interfacial requirements.

4. Carry out extensive testing and life modelling to investigate both the space charge trapping properties and the long-term life performance, in order to define suitable levels for the design field and reach cost-effective designs associated with the desired life and reliability levels.

In addition, there is a need to investigate innovative condition monitoring techniques to be applied to cable systems in order to provide dynamic health condition information, which are particularly important considering the use of new materials and technologies and the type of waveform, often not perfectly DC, with harmonics, transients and so on, especially when renewables are involved.

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