

Falke Balland Lundevall

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Bachelor's thesis in BKJ
Supervisor: Mari-Ann Einarsrud
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Faculty of Natural Sciences
Department of Chemistry





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Author:

Falke Balland Lundevall

Supervisor:

Professor Mari-Ann Einarsrud

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Abstract

A semi-wet design of high voltage subsea cables (HVSC) has been investigated as a substitute of a dry design through analyses of water treeing, space charge accumulation and impurities in the crosslinked polyethylene (XLPE)-insulation. Additionally, polypropylene (PP) was discussed as a possible alternative to XLPE-insulation with respect to environmental concerns and insulating properties.

A water barrier of lead is frequently used in high voltage subsea cables to prevent water ingress and water treeing in the XLPE-insulation. As an alternative, the employment of dual polymeric outer layers has been shown to prevent water treeing several years beyond the projected lifespan of the cable. This is achieved by prolonging the time to reach a relative humidity of 70%, which is necessary for water trees to initiate. With a low water permeability outer jacket and a high water solubility inner jacket, numerical calculations simulated that a relative humidity of 70% was first achieved after 300 years under the influence of a thermal gradient.

Water trees are one of the main reasons for premature cable failure in high voltage subsea cables with XLPE-insulation and can be divided into vented and bow-tie water trees. Vented water-trees initiate from either the conductor or semi-conductor, while bow-ties initiate from defects and by-products. The by-products from peroxide-crosslinking of the XLPE insulation material, such as acetophenone, α -methylstyrene and α -cumylalcohol were found to cause space charge accumulation due to the entrapment of charge-carriers. Space charge accumulation was found to be enhanced in the presence of moisture, highlighting the importance of the water barrier design. α -cumylalcohol and water function as shallow traps, increasing conductivity and cause loss of dielectric properties. Therefore, by-products from crosslinking must undergo degassing which is not necessary for PP-based insulation.

Polyolefin elastomers (POE) were shown to improve the brittleness of iPP, giving iPP its desired properties for cable insulation as well as recyclability. As a result, iPP/POE blends could be a suitable alternative to XLPE-insulation. However, it has been reported that an increase in elastomer-content could significantly increase electrical treeing.

Contents

1	Introduction	1
1.1	Aim of thesis	1
2	Theory	2
2.1	Design of high voltage subsea cables	2
2.1.1	Water barrier for HVSC	3
2.2	Semi-wet design of HVSC	3
2.3	XLPE as electrical insulating material	4
2.3.1	Peroxide-crosslinking of PE	5
2.3.2	Degassing of XLPE-cable	8
2.3.3	Space charge accumulation in XLPE	8
2.3.4	Mechanical properties of XLPE	9
2.4	Water treeing in XLPE	10
2.4.1	Formation of water trees	12
2.4.2	Diffusion of water through polymeric sheath	12
3	Discussion	14
3.1	Aging of semi-wet high voltage subsea cable	14
3.1.1	Water ingress through layered water barrier sheath system	14
3.1.2	Growth of water trees under thermal cycling	15
3.1.3	Space charge accumulation in the presence of moisture	16
3.1.4	Methane-formation and degassing of cable	17
3.2	Alternatives to dicumyl peroxide as crosslinking agent	17
3.3	Environmental concerns of XLPE and alternatives	18
4	Conclusion and future perspectives	20
	References	22
	Appendix	29
A	Arrhenius parameters for diffusion and solubility constant	29

1 Introduction

In light of emissions from non-renewable resources, the world is experiencing detrimental effects such as rise of sea level, extreme weather and famine [1]. The emission of CO₂ and other greenhouse gasses are the leading cause of global warming and are a result of the combustion of fossil fuels [2]. The emission rate of CO₂ has never been higher and is a consequence of the immense energy demand worldwide [3, 4]. A possible solution for the ongoing climate crisis is the use of renewable energy sources, such as wind energy [4].

The solution depends on a reliable and efficient power transmission system, made up by high voltage power cables, and it is therefore crucial for achieving a sustainable energy consumption [5]. With higher wind speeds offshore relative to onshore, a higher efficiency is to be expected of offshore wind farms and can be obtained by such a power transmission system [6]. For that reason, several wind farms are to be developed by 2030 in the Nordic and Baltic seas with a capacity of 45 GW and 8 GW, respectively [6]. The power transmission system also gives the possibility to connect the European electricity market together, and it provides the means to sell clean energy to countries which do not have the same opportunities for harvesting their own [5]. An example of this is Norway's connection with Denmark, the Netherlands and soon Germany, achieved by subsea power cables, which takes advantage of Norway's water reservoir and its hydroelectric power capabilities [5, 7].

The high voltage subsea power cables are protected by water barriers to prevent water ingress, since this could lead to cable failure [8]. Watertight barriers made of metal, usually lead, are recommended in subsea power cables with a voltage above 36 kV [8, 9]. Nevertheless, the European union (EU) wishes to ban the usage of lead because of health- and environmental reasons, and an alternative water barrier is sought-after [10].

1.1 Aim of thesis

The aim of this thesis is to discuss a semi-wet design of high voltage subsea cables and if a polymeric water barrier can be a suitable and reliable solution with XLPE-insulation. The thesis will first give an overview of the cable and focus its attention to XLPE as

an insulating material. Crosslinking of PE and its by-products will be emphasized. Thereafter, the thesis will explain the process of water treeing and how water diffuse through the polymer material. The thesis deals with space charge accumulation and how it is influenced by impurities and water. Lastly, the thesis discusses alternatives to XLPE as insulation and the consideration of PP-based insulation.

2 Theory

2.1 Design of high voltage subsea cables

High voltage subsea cables (≥ 36 kV) are essential for transporting power between off-shore power installations and to the mainland [11]. The transmission of power can be done by either a three-phase system, i.e. alternative current (AC), or single-phase direct current (DC) [5]. HVSC can be divided into static and dynamic cables, depending on the mechanical forces applied to the cable while in operation [12, 13]. Dynamic cables are usually directly connected to floating off-shore installations, e.g. wind turbines, and are therefore exposed to considerable amounts of mechanical forces [14]. Correspondingly, this requires the cable to be both resilient and flexible. Static cables are usually lied down on the seabed to connect the mainland with the intermediate link of the offshore installations and are therefore subject to minor mechanical forces [12]. HVSC are generally made up of a conductor, semiconductor, insulation, water barrier, armouring and an outer sheath [15]. Figure (1) shows a simple illustration of the design of an HVSC.

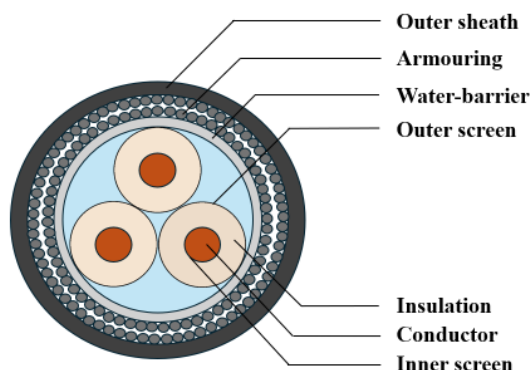


Figure 1: Cross section of a three-phase high voltage subsea cable

The conductor is responsible for carrying the current (i.e. power) and is usually made of copper (Cu) or aluminium (Al) because of their high electric conductivity, $\kappa_{\text{Cu}} = 58.4 \text{ MS m}^{-1}$ and $\kappa_{\text{Al}} = 37.0 \text{ MS m}^{-1}$, respectively [7, 16]. In figure (1), the conductor is coloured in orange and the three conductors display a three-phase system. The semiconductors are responsible for reducing the stress induced by the electric field as a result of the high voltage [17]. In figure (1) the semiconductors are referred to as inner- and outer-screen and reduces the induces stress by smoothing the conductor surface to prevent stress-enhancement in the ridges and grooves of the conductor [18]. The insulation ensures that the current can flow smoothly through the cable without dissipating power. It also prevents short-circuiting between the conductor and other electric conductive material of which the cable consists [18]. The insulation surrounds the conductors in figure (1) and is coloured in beige. The armouring provides mechanical strength and stability to the HVSC with the means of metal wires coated with zinc and bitumen to prevent corrosion [18]. Since the anti-corrosion layer becomes less prominent in the presence of scratches, HVSC usually consist of an outer polymeric sheath [18].

2.1.1 Water barrier for HVSC

The water barrier is responsible for preventing water ingress into the cables' insulation and is shown in figure (1). Water ingress has been studied extensively as it may cause degradation of the insulation and electrical breakdown [8, 19]. The barrier is usually made of lead because of its ductility, low cost and great stability in the presence of water [8, 15, 20]. Furthermore, lead's density of $207.20 \text{ g mol}^{-1}$, makes it a favorable water barrier in static applications [16, 18]. A metallic water barrier made up by aluminium or copper can also be a possibility, but they are not commonly used since aluminium is prone to corrosion while copper is very expensive [18].

2.2 Semi-wet design of HVSC

Subsea cables are usually distinguished from each other with respect to their design of the water barrier and could either be of a dry, semi-dry, semi-wet or wet design [15]. A metallic water barrier is regarded as a dry design of the subsea cable. A dry design of subsea cables

is on the other hand not desirable for dynamic applications and environmental reasons due to lead's poor mechanical properties and the possibility of marine pollution of heavy metals [15, 21, 22]. Furthermore, the considerable density of lead can exert strain on the cable-connections [21]. Based on these reasons, alternatives have been sought after, and a semi-wet design has shown promising results [23]. Semi-wet design implies a polymeric water barrier and can contain water-absorbing agents to limit water ingress [15, 18]. The polymer will however inevitably lead to water ingress in contrary to a dry design of subsea cables [15, 18, 24]. A polymeric water barrier is not unusual in medium-voltage subsea power cables (≤ 36 kV) since the water ingress is of little concern with respect to the small electric field strength, but this is not the case for high-voltage subsea power cables [18].

2.3 XLPE as electrical insulating material

Cross-linked polyethylene (XLPE) is frequently used as insulation-material in high-voltage applications because of its good dielectric, chemical and thermal properties, flexibility, toughness and low price [25, 26]. Ethylene is the monomer which produces polyethylene (PE) by bonding with other ethylene-molecules [27]. By crosslinking PE, one transforms the polymer from a thermoplastic to a thermoset polymer [26]. This implies that XLPE will chemically decompose at elevated temperatures, and the crosslinking of PE is therefore irreversible [26]. In figure (2) it is possible to see the structure of ethylene, n-number of ethylene molecules creating polyethylene and XLPE.

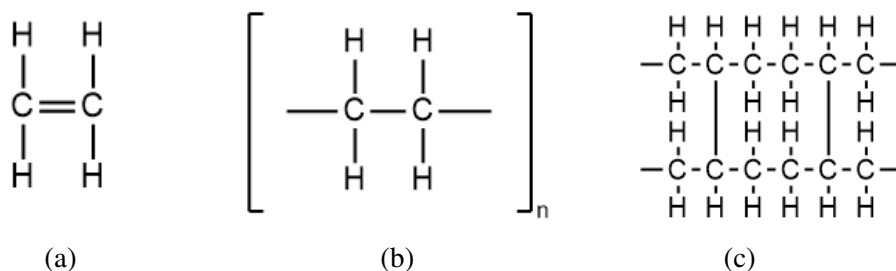


Figure 2: Ethylene (a), n-number of ethylene molecules bonded together to form polyethylene (b) and crosslinked polyethylene, XLPE (c), drawn in ChemDraw.

XLPE can be attained by either irradiation-, peroxide- or silane-crosslinking of PE [25]. One of the main reasons for crosslinking PE is to achieve an insulation material with

a higher heat resistance than PE itself [28]. This will result in a higher power transfer since transferring more power demands a higher operational temperature, whereas the operational temperature of PE and XLPE is 75 °C and 90 °C, respectively [25, 27]. The properties of XLPE are shown in table (1) together with different polymers for comparison [26].

Table 1: Properties of XLPE and several different polymers, also used for insulation, such as low-density polyethylene (LDPE), high-density polyethylene (HDPE) and ethylene propylene rubber (EPR). The dielectric constant and loss factor were determined at 60 Hz. The table has been reproduced with the courtesy of Springer Nature [26]

Properties	XLPE	LDPE	HDPE	EPR
Electrical resistivity [Ωm]	$> 10^{13}$	$> 10^{14}$	$> 10^{13}$	$10^{13} - 10^{15}$
Dielectric strength [MV m^{-1}]	22	18.5-28	18-20	36
Dielectric constant	2.30	2.30	2.35	3.17-3.34
Dielectric loss factor, $\tan \delta$, (10^{-3})	0.3	0.2	0.2	7.3
Density [g cm^{-3}]	0.920	0.910-0.925	0.941-0.965	0.860
Melting temperature [$^{\circ}\text{C}$]	90-110	110	130	$> 150^{(a)}$
Modulus of elasticity [MPa]	790	117-242	552-1035	210-470

(a) The melting point of EPR was found in [29]

2.3.1 Peroxide-crosslinking of PE

There are several advantages and disadvantages with each crosslinking method as mentioned, but peroxide-crosslinking stands out as superior because of the high quality of insulation-material while using well established technology [26, 27]. Furthermore, peroxide-crosslinking produce thicker insulation-material than irradiation- and silane-crosslinking, which is desirable in high voltage cables [30]. The initiation step for peroxide-crosslinking is done by thermolytic decomposition of peroxides to make free radicals. The single covalent bond between the two oxygen atoms is usually cleaved because of the low bonding energy (~ 150 kJ/mol) in comparison with carbon-carbon (~ 350 kJ/mol) and carbon-hydrogen bonds (~ 415 kJ/mol) [26]. By hydrogen abstraction, the alkoxy radicals ($\text{RO}\cdot$) react with the PE-substrate (PH) resulting in radicals of PE, given in equation (1) [26].



The final step of peroxide-crosslinking is the termination reaction between two PE-radicals, producing XLPE, illustrated by equation (2) [27].



Dicumyl peroxide is the most common crosslinking-agent in peroxide-crosslinking, but in recent years Bis(tert-butylperoxy) (BIPB) has been recognized as a potential substitute [31]. The thermal decomposition of dicumyl peroxide is given in figure (3) and will be focused onwards [27].

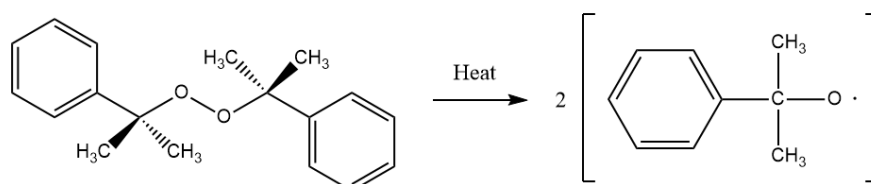


Figure 3: Thermal decomposition of dicumyl peroxide producing two cumyloxy, drawn in ChemDraw

Following the general reaction given in equation (1), cumyloxy will take a hydrogen atom from PE by hydrogen abstraction and produce the PE-radical and cumyl alcohol [32]. The PE-radical will subsequently form the crosslinked product as stated in equation (2). Following these simple reaction steps, one can observe the formation of cumyl alcohol as a by-product, but β -scission of cumyloxy is also possible, leading to the formation of acetophenone as another by-product, given in figure (4) [32, 33]. The activation energy for the hydrogen abstraction given in equation (1) is approximately 25 kJ/mol and therefore favoured over β -scission of cumyloxy with an activation energy of around 40 kJ/mol [26]. Nonetheless, with high enough temperature, a significant amount of β -scission reaction mechanism can take place, forming radicals of hydrocarbons with lower energy than cumyloxy [26].

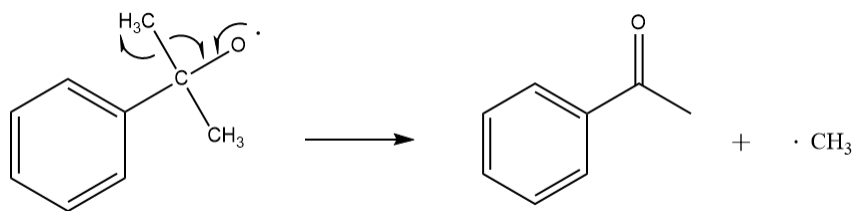


Figure 4: β -scission of cumyloxy, producing acetophenone and methyl radical, drawn in ChemDraw.

The methyl radical can follow the general equation (1) resulting in the formation of methane and subsequently give rise to a crosslinked product with the general equation (2) [32]. α -Methylstyrene is another by-product of dicumyl peroxide, resulting from the dehydration of cumyl alcohol, and is given by figure (5) [30].

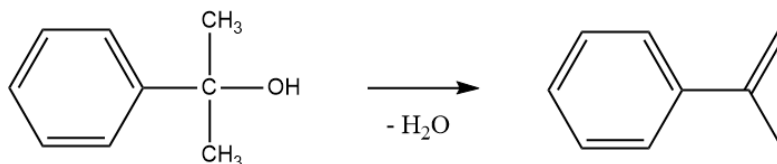


Figure 5: Dehydration of cumyl alcohol resulting in α -methylstyrene, drawn in ChemDraw.

The by-products enlisted are those of highest concern with respect to their concentration, and repercussion on the properties of the insulation, is given in table (2) with the exception of water and methane.

Table 2: The chemical name, structure and properties of the most significant by-products from peroxide-crosslinking, drawn in ChemDraw

Chemical by-products	α -Cumyl alcohol	Acetophenone	α -Methylstyrene
Chemical structure			
Wt% in XLPE cable [30, 32]	1.2	0.6	0.02
Dielectric constant [30]	9.7	17	3.8
Conductivity [$S\ m^{-1}$] [30]	1.4×10^{-7}	2.4×10^{-4}	3.6×10^{-9}

2.3.2 Degassing of XLPE-cable

The byproducts produced by the peroxide-crosslinking are taken care of by degassing the cable to ensure an even distribution of the byproducts in the outer layer of the XLPE-insulation [32]. An even distribution of byproducts is achieved by applying a high external pressure at elevated temperatures, which prevents the byproducts from forming voids in the electric insulating material, potentially leading to electrical failure [32]. An even distribution is desirable because residual mechanical stress from the cable manufacturing, by-products, cavities and water-bubbles acts as stress-points in the insulation and can initiate degradation-mechanisms [34]. An even distribution of the byproducts would also make it easier for the byproducts to inevitably diffuse out of the insulation-material and make sure that the XLPE will maintain its desired dielectric properties [32].

2.3.3 Space charge accumulation in XLPE

XLPE is the insulating-material most commonly used in HVSC considering XLPE's great dielectric properties, but as a result it is vulnerable to the accumulation of space charges which can lead to cable failure [35, 36]. Since the insulation has a low charge carrier mobility, i.e. non-conductive material, the charge-carriers (electrons, holes and ions) will be trapped in the material [30, 35]. Consequently, this will lead to points in the material with high electric stress and delocalize the electric field distribution [30, 35]. Hence, the local field has been observed to become eight times as large as the applied electric field, causing electrical treeing and cable failure [36].

The accumulation of space charges can be mathematically derived by applying the differential form of Gauss law, equation (3), in combination with ohms law, equation (4). By assuming the charge to be conserved, equation (5) is derived [37, 38].

$$\nabla \cdot \vec{E} = \frac{\rho}{\epsilon} \quad (3)$$

$$\vec{J} = \sigma \vec{E} \quad (4)$$

$$\rho + \frac{\epsilon}{\sigma} \frac{\partial \rho}{\partial t} = \vec{J} \nabla \frac{\epsilon}{\sigma} \quad (5)$$

Here \vec{E} denotes the electrical field, ρ is the space charge density, ϵ is the permittivity, \vec{J} is the current density, σ is the conductivity and t is the time [37]. By observing equation (5), it is possible to see how space charge is related to permittivity and conductivity. While the permittivity in most insulating polymers remains more or less constant, the conductivity is on the other hand highly dependent on temperature [37, 39]. By assuming that a thermal gradient will be established under operating, this will lead to the accumulation of space charge, as a result of a conductivity-gradient [37]. The non-linear correlation between permittivity and conductivity can also be observed between interfaces such as in the dielectrics components of the cable, impurities in the XLPE-insulation and between amorphous and crystalline regions in the insulation. These interfaces can function as potential sites of space charge formation and accumulation [37]. Another example of space charge accumulation was reported by Bezille et al. where a diffusion of impurities from the semi-conductor was observed into the insulation, under the cable manufacturing. This resulted in a higher conductivity with a more or less constant permittivity [37, 40].

The generated traps can be described as shallow or deep, indicating how strongly the trap retains the charge carrier. Shallow- and deep traps are distinguished with their corresponding energy states of 0.1-0.3 eV and 0.8-1.4 eV, below the conduction band of the polymer [30]. The by-products of peroxide-crosslinking are one of the main reasons for space charge accumulation in XLPE and are therefore of high concern regarding premature cable failure [41]. Acetophenone and α -methylstyrene induces deep electron traps, while water and hydroxyl-groups, such as α -Cumyl alcohol, induce shallow traps [42, 43, 44].

2.3.4 Mechanical properties of XLPE

The chains of ethylene can order itself to a different degree and it is common to distinguish between amorphous- and crystalline regions. If the ethylene-chains are ordered in a crystalline matter, the ethylene-chains are placed parallel to each other, resulting in a systematic structure. On the other hand, amorphous regions denote areas of ethylene-chains which seem random and non-organized [27]. An illustration of the amorphous and crystalline

regions are given in figure (6).

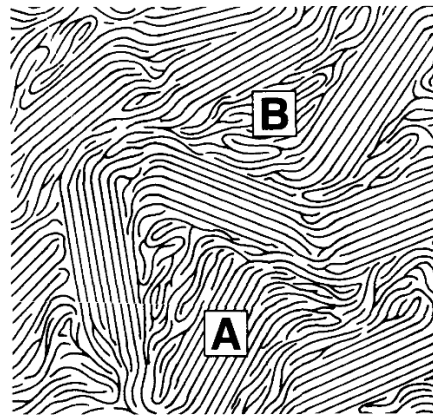


Figure 6: Crystalline (A) and amorphous (B) regions of polyethylene. The figure has been reproduced with permission from IEEE [27]

Both the amorphous- and crystalline regions give PE and XLPE the desired mechanical properties as an insulating material. Amorphous regions give flexibility to the material while crystallinity makes it hard and dense. By making the polymer denser, it will be less susceptible to diffusion of gasses [27].

2.4 Water treeing in XLPE

Water treeing is a phenomenon which can possibly lead to cable failure due to water ingress into the insulation, leading to short-circuiting of the material because of the higher conductivity than the insulation itself [8]. Water trees are water-filled tunnels (i.e. cavities) in the insulation and figure (7) illustrates how water trees can appear in the XLPE-insulation [45]. Water trees are one of the biggest causes of high voltage subsea cable failures, but have recently received a lot of attention, which has led to fewer failures due to higher purity of the insulation and better cable-designs [8]. Water trees can be divided into two groups, vented or bow-tie, depending on the origin of formation and are given in figure (7a). Vented water trees form at either the conductor or insulation screen and can grow to a significant length, given in figure (7b). Bow-tie trees form at either deformities or impurity-sites in the insulation and are given in figure (7c) [8]. Vented water trees are usually of more concern than bow-tie trees because of vented water trees ability to achieve lengths which can connect the conductor together with the semiconductor, as illustrated

in figure (7b). Furthermore, the purity of the insulation has seen much progress over the years, limiting the formation of bow-tie trees [8].

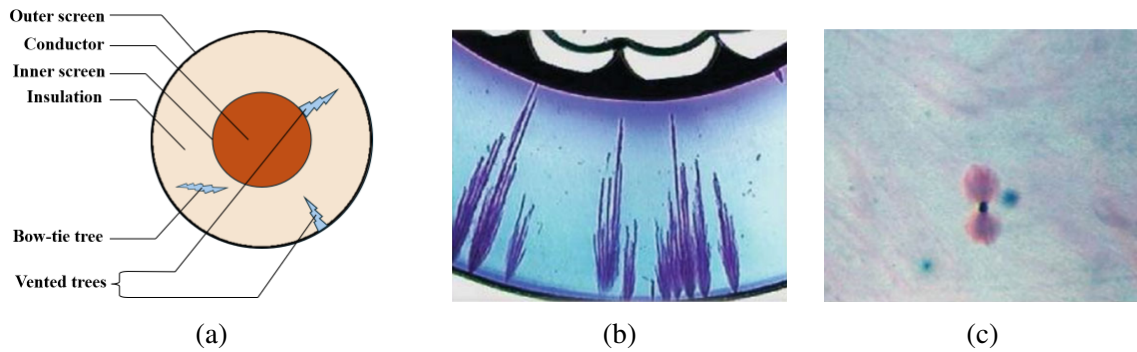


Figure 7: (a) Illustration of vented and bow-tie water trees in XLPE-insulation, (b) vented water trees in XLPE-insulation, growing from the outer-screen, (c) bow-tie water tree in XLPE-insulation, growing from an impurity. Figures (b) and (c) have been reproduced with permission from Springer Nature [46]

Electrical trees are another possible "treeing"-degradation mechanism of HVSC, capable of causing cable failure [47]. As a result of high voltage and consequently high electric stress, the dielectric insulation can locally break down, referred to as partial discharge. Breakdown of the insulation can then function as an initiation point for electrical trees [34, 47]. Furthermore, water trees can also function as initiation points for electrical trees. In contrast to water trees, electrical trees form hollow tunnels (i.e. cavities) as a result of the insulation decomposing from the partial discharge [47, 48].

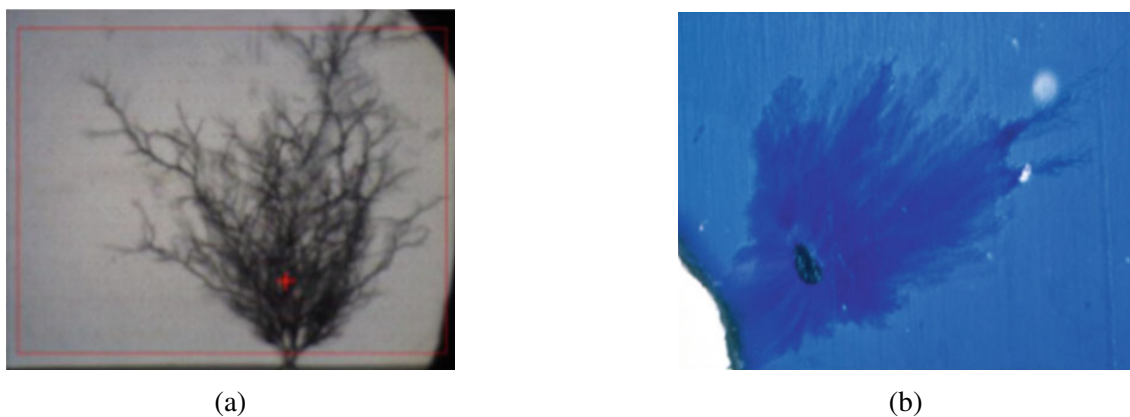


Figure 8: (a) Illustration of electrical tree and (b) illustration of electrical tree initiated from a water tree. Figures (a) and (b) have been reproduced with permission from Springer Nature [46]

2.4.1 Formation of water trees

The formation of water trees in the XLPE-insulation demands the presence of an electric field, water and deformities [23]. A power cable will inherently always consist of an electric field, but in addition to the previous stated criteria, the relative humidity must be above 70% for water trees to be formed [49, 50]. Wet and semi-wet cable designs of high voltage subsea cables take advantage of the relative humidity threshold with the help of an insulating system prolonging the time to reach 70%. By doing so, the cables projected lifespan can be increased [21, 51]. The application of two outer jackets, one with low water permeability and one with high water solubility, can complement each other and make an ideal design for prolonging the time to reach a relative humidity of 70% [19].

2.4.2 Diffusion of water through polymeric sheath

Since a polymeric sheath will not be entirely watertight and the consequence of water ingress could lead to cable failure, the diffusion of water through the polymeric sheath has been thoroughly investigated [24, 19]. The polymeric type and structure, as well as temperature, will decide how much water which can be diffused through the polymer material [19]. The polymeric dependency is usually expressed as a solubility coefficient, S , and gives rise to the following equation:

$$q = S \cdot p \quad (6)$$

where q is defined as the mass of water absorbed per unit volume and p is defined as the partial water pressure just above the polymer surface. Equation (6) is reduced to Henrys' law if the solubility coefficient is not dependent on the partial pressure [19].

Ficks first law states that a flux will go from an area of higher concentration to an area of lower concentration, and for HVSC with a polymeric sheath, the diffusive mass flux of water is usually said to follow this law [19, 52]. The law explains that the diffusive mass flux of water, j , can be expressed as the multiplication of a diffusion constant, D , and the gradient of mass of water absorbed per unit volume [45]. Ficks first law is given by

equation (7).

$$j = -D\nabla q \quad (7)$$

As mentioned, the diffusion of water is dependent on temperature and is included in both the solubility and the diffusion constant with an Arrhenius-relationship, given in equation (8, 9)[19, 45].

$$S(T) = S_0 e^{-\frac{E_S}{RT}} \quad (8)$$

$$D(T) = D_0 e^{-\frac{E_D}{RT}} \quad (9)$$

The Arrhenius-relationship is given by the pre-exponential factors S_0 and D_0 , activation energies E_s and E_D while R is the universal gas-constant and T is the temperature in Kelvin. Since the diffusion of water through the polymer must fulfill the continuity equation, the time evolution of water concentration in the polymer can be calculated numerically. This is achieved by equation (10), which incorporates (6) and (7) as well as the temperature-dependencies in the solubility- and diffusion coefficient in equation (8) and (9) [19].

$$S \frac{\partial p}{\partial t} + \nabla \cdot (-D\nabla Sp) = 0 \quad (10)$$

However, it is reasonable to expect a thermal gradient from the conductor to the outer sheath when transferring current, which is not included in equation (10) [19, 45]. The radial mass flow of water under the influence of a thermal gradient, can therefore be expressed as given in equation (11) [19].

$$j_r = -D \frac{1}{r} \frac{\partial Sp}{\partial r} = 0 \quad (11)$$

3 Discussion

3.1 Aging of semi-wet high voltage subsea cable

3.1.1 Water ingress through layered water barrier sheath system

Hellesø et al. calculated the time to reach a relative humidity level of 70% in the XLPE-insulation with different order and dimensions of two polymeric outer jackets, by applying equation (10) [19]. One of the jackets had low water permeability (LP) while the other had a high water solubility (HS). The authors made several cases, which involved different combinations of the two outer jackets and highlighted three, given in table (3). The calculations were carried out at two uniform temperatures and under the influence of a thermal gradient. The uniform temperatures were 5 °C and 25 °C while the temperature-gradient was achieved by including equation (11), which ensured 50 °C at the conductor core to 5 °C at the outer sheath.

Table 3: Three cases of material-jackets with different arrangements and their respective time to reach a relative humidity of 70% at three different temperatures of 5 °C, 25 °C and under the influence of a thermal gradient, from 50 °C to 5 °C, denoted by ∇ °C. The table has been reproduced with the courtesy of Applied Polymer science, Wiley Periodicals [19].

Case	Inner material (thickness) [mm]	Outer material (thickness) [mm]	Time to reach RH-level at 70% [years]		
			5 °C	25 °C	∇ °C
1	-	LP (6.2)	170-200	14-16	95
2	HS (3.1)	LP (3.1)	380-410	30-32	300
3	LP (3.1)	HS (3.1)	89-110	7-9	26

Using the assumption that the cable will experience a thermal gradient for most of its lifetime, table (3) shows promising results for a layered water barrier sheath system. The lifetime of a submarine power cable is dependent on several factors and is therefore difficult to estimate, but a lifetime of 30-40 years is regarded as probable if well-protected [18]. With an estimated lifetime of 30-40 years, table (3) displays the possibility of water ingress to be of no concern since the formation of water trees will occur several years after its projected lifespan. It is worth mentioning that the paper describes the cable

which underwent the given simulations as a wet design. Nonetheless, the cable consists of different outer jackets preventing moisture to impregnate the insulation and can therefore be classified as a semi-wet design after the definition given in [15].

Case 2 achieves the longest time period to reach an RH-level of 70% for all examined temperatures, resulting in the most suitable design of the three for preventing water trees. Case 3 distinguishes itself from the two other cases for consistently being the case with the shortest time to reach an RH-level of 70% and therefore be the least suitable design of the three for preventing water trees. Case 3 showcases the importance of the arrangement of the two jackets and probably achieves such a short time to reach an RH-level of 70% as a result of the jacket of high solubility being quickly saturated [19]. Case 1 also displays the importance of sheath thickness in comparison with case 3 for consistently achieving a longer time period to reach an RH-level of 70% even though case 1 has no high solubility jacket. The low-permeability jacket of case 1 is thicker than in case 3 and if the high-solubility jacket of case 3 becomes quickly saturated, it seems that the only protecting layer that is left is the low-permeability jacket, favoring a higher thickness.

3.1.2 Growth of water trees under thermal cycling

Hellesø et al. showed that under the influence of a thermal gradient, the cable reaches an RH-level of 70% several years after the cable with uniform temperature of 25 °C, implying that a thermal design of the cable is also of great importance [19]. The analyses given by Hellesø et al. focus their attention on preventing the formation of water trees under isothermal temperatures, by assuming a constant thermal gradient. It is however useful to analyse the growth of water trees under varying temperatures if the cable has reached an RH-level of 70%. The high voltage subsea cables of wind farms experience variable loading which results in thermal cycling [53]. As the temperature of the insulation increases, so does water vapour content. By decreasing the temperature, the saturation limit for water vapour in the insulation will follow, resulting in water being condensed and fill cavities in the insulation (i.e. water trees) [53]. By analysing water tree content under thermal cyclic conditions, the concentration of bow-tie water trees increased by ten-fold and the length of vented water trees also increased, when compared to the same analyses under isothermal conditions [53, 54]. One explanation for this is the temperature dependency of

water diffusion and solubility, given by the Arrhenius-relationship in equation (8) and (9).

3.1.3 Space charge accumulation in the presence of moisture

Since a semi-wet design of HVSC is more susceptible to water ingress compared to a dry design, space charge's influence was studied in a semi-wet design and was observed to enhance each other, capable of causing premature cable failure [55, 56]. Li et al. highlighted several observations when water treed XLPE-insulation was under the influence by AC-peak-voltage of 7 kV; a proportionality between water moisture and space charge density, as well as between total space charge density and applied voltage [55]. The space charge density was highest at the tip of the water trees [55]. An applied voltage of 7 kV is regarded as a medium-voltage-level, but Li et al. concluded with a direct proportionality between space charge density and applied voltage [55]. Their findings can therefore be assumed to be applicable for high voltages [55]. Stancu et al. reported an increase in dimensions of the water trees and in the average space charge density when the polymeric cable insulation was exposed to AC-voltage in an aqueous environment [56]. Stancu et al. proposed that the increase in average space charge density is a result of a higher concentration of ions in the water treed areas and at the interfaces between the water trees and the insulation network [56].

Water and α -cumyl alcohol are regarded as shallow traps and can therefore facilitate for charge-carrier mobility, i.e. increase conductivity and decrease the dielectric properties of the XLPE insulation [37, 57]. Since the trapping energies of water and α -cumyl alcohol are more or less the same as the interface energy of the amorphous regions, they can act as bridging-elements and therefore increase conductivity [44]. At the interface between the insulation and the semiconductor, a diffusion of impurities consisting of carbonyl-groups was reported by Bezille et al.[40]. The nature of these impurities gave the possibility of space charge accumulation [40]. Non-ionic impurities have the ability to act as traps whereas ionic can increase charge-carrier mobility. Furthermore, the ionic-impurities will diffuse more rapidly into the insulation if water is present and if the impurities are water-soluble, such as carbonyl-groups [37]. However, the number of impurities in the insulation and semiconductors are regarded as small by today's standards, leaving its adverse effects to a minimum [37]. Nevertheless, space charge accumulation emphasizes the importance of

purity in both the insulation and semiconductor [37].

3.1.4 Methane-formation and degassing of cable

Methane is one of the by-products of peroxide-crosslinking and is of high concern regarding its flammability [32]. Methane is liberated from the XLPE-insulation while the cable is under operation, but becomes trapped by the protective water barrier [32]. The methane can thereafter travel along the cable, exerting pressure to the joints and terminations [32]. To reduce the amount of methane in the XLPE-insulation, the cable must undergo degassing.

One important aspect of the degassing of the XLPE-cable is to ensure that the cable maintains its reported properties since the byproducts will inevitably diffuse out of the insulation, capable of altering them [32, 58]. By degassing the cable and making sure that the byproducts have been diffused out of the insulation-material, its true properties can be determined by testing of the cable. By doing so, one can guarantee that its properties stay the same while in operation. A profound example of this was reported by Andrews et al. where by-products of peroxide-crosslinking greatly improved the high-field breakdown strength by 75% in both wet and dry designs of power cables, but after 16 weeks the improvement was insignificant [32].

3.2 Alternatives to dicumyl peroxide as crosslinking agent

Dicumyl peroxide is utilized in peroxide-crosslinking due to its low activation energies and kinetics, but it produces several undesirable by-products which need to go through degassing, leading to the search for alternatives [59]. Instead of cumyloxy radicals, the t-butyl alkoxy radical can also crosslink PE, but it produces lighter by-products which are easier to remove, and it reduces the formation of methane [59]. Chen et al. compared Bis(tert-butylperoxy) (BIPB) against dicumyl peroxide and reported a slower growth rate and shorter lengths of electrical trees when BIPB was the crosslinking-agent [31]. Bis(1-(tert-butylperoxy)-1-methylethyl)-benzene is a possible crosslinking-agent, producing the t-butyl alkoxy radical, shown in figure (9) [60].

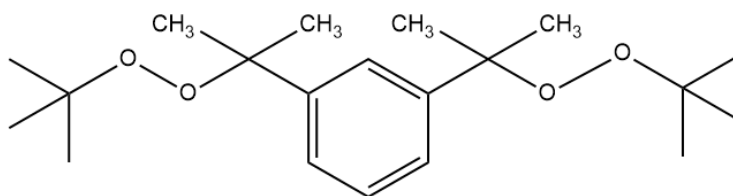


Figure 9: Chemical structure of bis(1-(tert-butylperoxy)-1-methylethyl)-benzene, producing oxyl-radical for peroxide-crosslinking, drawn in ChemDraw.

Chen et al. speculated that BIPB could potentially have a higher efficiency than dicumyl peroxide and predicted that BIPB would take over for dicumyl peroxide as the main choice of crosslinking-agent [31]. However, Sun and Person reported that the activation energies of t-butyl alkoxy radicals are inferior to cumyloxy and will negatively affect the kinetics of the crosslinking-process to a great extent [59]. An alternative to limit the formation of methane is the substitution of the methyl-groups in dicumyl peroxide with long alkyl chains [59]. However, this will greatly reduce the amount of radicals and consequently limit the process of crosslinking since the production of methyl radicals with respect to figure (4), will be limited [59].

3.3 Environmental concerns of XLPE and alternatives

When PE is crosslinked, the polymer is thermoset and gives the polymer its desired properties, but it makes the material highly difficult to recycle [26]. Metal recovery is prioritized when recycling a power cable while the insulation-material is usually incinerated or sent to land fill [61]. Bawareth et al. reports that the salt river project in Arizona, USA, produces approximately 540 tons of XLPE each year and the incineration of one ton of XLPE produces three tons CO₂ [61]. Ashihara et al. reported that with the use of supercritical 1-propanol, one could recycle XLPE-insulation completely, but it was limited to cross-linked PE from silane-crosslinking [62]. However, silane-crosslinking is not applicable for high-voltages since a thick insulation is required [30]. Recycling methods such as decrosslinking with supercritical-fluids are therefore possible, but generally not economically sustainable nor practical [26, 61]. As a result, alternatives to XLPE-insulation are sought after and blends of LDPE and HDPE, as well as blends of PE and polypropylene (PP) have shown promising results [63]. The blend of PE and PP distinguishes itself as an

excellent substitute because of the high operational temperature of 110°C and the polymerization of PP is given in figure (10) [63]. Since PP-based insulation has a high operational temperature, no crosslinking-mechanism is necessary, eliminating the crosslinking by-products from the insulation [63]. Consequently, the space charge accumulation from impurities in the insulation becomes greatly reduced. Furthermore, making degassing of power cables not necessary which is a complicated and time-consuming process [63].

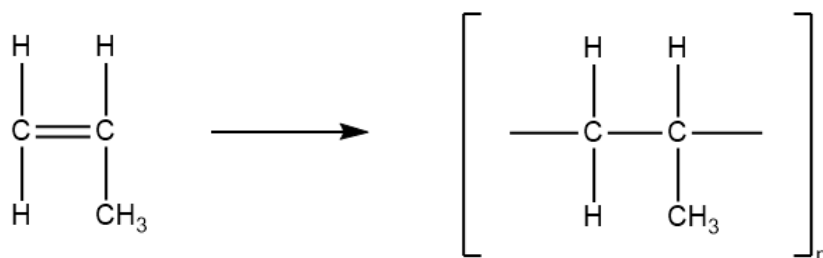


Figure 10: Polymerization of propylene monomer to polypropylene (PP), drawn in Chem-Draw

Both blends are thermoplastic and therefore recyclable [63]. As a result of the methyl-group in polypropylene, the polymer can be divided into three different configurations, isotactic PP (iPP), syndiotactic (sPP) and atactic (aPP), which give rise to different properties [63]. PP-based materials have excellent insulation-properties, but experience undesired brittleness and stiffness at low temperatures [64]. By blending iPP with Polyolefin elastomer (POE), the flexibility becomes highly improved with no significant drop of operational temperature [64, 65]. Table (4) shows electrical and mechanical properties of PP and blend of iPP/POE with XLPE as comparison.

Table 4: Mechanical and electrical properties of PP and iPP/POE blends with XLPE for comparison [63], [65] and [64].

Properties	PP	iPP/POE blends	XLPE
Elongation at break [%]	501	953	600
Tensile yield strength [MPa]	35	20.9	22.0
DC electric resistivity [Ωm]	2.2×10^{16}	4.4×10^{17}	0.9×10^{15}
DC breakdown strength [kV mm^{-1}]	400-600	325	300
Working Temperature [$^{\circ}\text{C}$]	110	100-120	90
Melting temperature [$^{\circ}\text{C}$]	165	-	105 (softening)

Table (4) illustrates how iPP/POE blends could be a suitable choice for cable-insulation,

but Yuan et al. reported that an increase of elastomer-content up to 30 wt%, in PP-based insulation-materials, significantly enhanced the growth rate of electrical treeing [66]. Yuan et al. investigated the propagation of electrical trees when an AC voltage of 8 kV_{rms} was applied, but since electrical trees are dependent on applied voltage, its adverse effect may become more evident when in use of high voltage cables [67]. Additionally, a semi-wet design is more susceptible to water-treeing than a dry-design, and as a result, it can produce more initiation points for electrical trees.

4 Conclusion and future perspectives

A semi-wet design of a high voltage subsea cable has the capability to replace the traditional dry-design and still function as intended while eliminating the possible pollution of lead. Water ingress is inevitable, but proper choice of polymeric water barrier design can prolong the time to reach a relative humidity of 70%, which is necessary for the formation of water trees. Since moisture has been observed to be proportional to space charge density and the dimensions of water trees increase in the presence of applied high voltage, the restriction of moisture is essential for the application of semi-wet design.

Furthermore, the by-products of peroxide-crosslinking can function as stress-points in the XLPE-insulation, leading to space charge accumulation which may result in premature cable failure. Acetophenone and α -methylstyrene act as deep traps which can lead to space charge accumulation while water and by-products such as α -cumyl alcohol can increase the conductivity and reduce the dielectric properties of XLPE-insulation. Consequently, the cable must undergo degassing to improve the quality of the insulation. However, crosslinking is unnecessary for PP-based insulation, eliminating by-products from peroxide-crosslinking, making degassing of the cable not required. Additionally, PP-based insulation is recyclable in contrast to XLPE-insulation, but may experience higher growth-rates of electrical trees with increased elastomer-content.

With the development of subsea power cables, the international energy market becomes more prominent, making the distributing of clean energy both easier and more accessible across nations. By taking advantage of clean energy, the world takes one step closer to

a sustainable future with lower emissions, achieved by an efficient power transmission system, partly made up by high voltage subsea cables.

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Appendix

A Arrhenius parameters for diffusion and solubility constant

To include the temperature dependency in both the solubility- and diffusion-constant, equation (8) and (9) were applied by Hellesø et. al, and the values for the pre-exponential factors and the activation energies are given in table (5) [19].

Material	D_0 [m ² s ⁻¹]	E_D [kJ mol ⁻¹ K ⁻¹]	S_0 [kg m ⁻³ Pa ⁻¹]	E_S [kJ mol ⁻¹ K ⁻¹]
XLPE	3.30×10^{-1}	55.7	1.80×10^{-7}	-9.90
SC	2.55×10^{-2}	58.0	9.75×10^{-11}	-42.15
HS	2.77×10^{-6}	28.7	4.34×10^{-11}	-37.10
LP	1.40×10^2	81.37	7.21×10^{-11}	-35.92

Table 5: Table of pre-exponential factors D_0 , S_0 and activation energies E_D , E_S in the different materials used for calculating the time to reach 70% RH-level. The table has been reproduced with the courtesy of Journal of Applied Polymer science, Wiley Periodicals [19].

