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REVIEW

Failure of submarine cables used in high-voltage power transmission: Characteristics, mechanisms, key issues and prospects

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Abstract

This study reviews the failure of high-voltage submarine cables used in offshore power transmission and provides highlights of their failure characteristic, mechanisms, key issues and prospects. High-voltage submarine cables are designed and applied according to the high-voltage alternating current and high-voltage direct current requirements. Inevitably, the fault occurs in HV submarine cables that is different from that of an underground cable. External aggression remains the primary cause of faults, such as fishing and anchors. Most faults continue to occur at a shallow depth (300 m). The optical fiber inside the submarine cables plays a substantial role in the temperature and stress-strain monitoring and diagnosis. However, it is regarded as a weak point for electrical fault. Insulation breakdown is the leading reason for the short fault. The failure mechanism is complicated when associated with marine conditions. Some defects of insulation and extensive voids, water treeing, mechanical stress, partial discharges, overheating, and electrochemical erosion contribute to the insulation breakdown. Several key issues, including anchoring damage, treeing, defects, and thermal-electric ageing, are proposed. Prospects and new methods related to the cable failure, especially for insulation ageing by treeing and electrothermal effects, are also discussed.

1 | INTRODUCTION

Submarine cables are widely used for new energy power systems in marine environments, such as offshore wind, wave, and solar power transmission applications, and as a power supply to remote areas [1–2]. High-voltage alternating current (HVAC) and high-voltage direct current (HVDC) are the main types of power transmissions by submarine cables [1, 3]. Currently, submarine cables with long distances and high voltage carry high electric power between countries and offshore installations, such as oil/gas platforms and offshore wind farms [4–6].

Three-core submarine cable or three single submarine cables are employed for HVAC transmission. HVAC technology is simple and has high availability, but it lacks power control and requires reactive compensation [3, 7]. Besides, it has a limited distance for high power transmission with high efficiency. HVAC submarine cables are usually used for short-distance power transmission. HVDC is a promising technology for long-distance offshore power transmission, including line-commutated converter (LCC)-HVDC using thyristor and voltage source converter (VSC)-HVDC using insulated-gate bipolar transistor devices [8]. Due to the polarity reversal for reverse flow, the submarine cables used in LCC-HVDC transmission are usually mass-impregnated (MI) cables [9]. VSC-HVDC transmission systems present no polarity reversal for reverse flow, which is well suited for offshore applications due to its small footprint and environmental impact [10–11]. Usually, extruded cross-linked polyethylene (XLPE) submarine cables are used [1, 2]. However, it is reported that the substantial space charge accumulation in the polymer insulation by voltage polarity reversal threatens the use of extruded cables [12]. The submarine cables are usually located near the coast and are

TABLE 1 Examples of typical high voltage submarine cables [26–28]

Submarine power cable					
Rated voltage and rating	500 kV1500 MVA	±400 kV1000 MW	525 kV2 GW	±250 kV600 MW (bipolar)	450 kV700 MW
Structure and Insulation	Oil-filled paper insulationEthylene-propylene rubber semiconducting layer	Water barrierExtruded XLPE three-core AC cable with optical fiber	Water barrierExtruded XLPE insulation	Water barrier1 × 600 mm² DC-XLPE with optical fiber	Water barrierFlat mass-impregnated insulation with optical fiber
Application	High-voltage alternating current (HVAC) forOffshore power transmission	HVAC submarine link under the Dardanelles Strait	Long-distance high-voltage direct current (HVDC) power transmission	Line-commutated converter-HVDC Installed for Hokkaido - Honshu Line	HVDC forFeda (Norway) and Eemshaven (the Netherlands) link
Length	60km	65–124 km	>1500 km	42 km	1270 km

laid under shallow water (~200 m) [3]. To protect the submarine cables from third-party damage, they are buried under the seabed (~1–3 m) [1–3]. High-voltage (HV) submarine cables are subjected to complex conditions, such as anchoring (mechanical stress), salt mist, water pressure, thermal stress, and chemical corrosion [3, 13]. Submarine cables can inevitably be damaged under complex working conditions, such as fishing, anchoring, ocean current, tsunami, corrosion, and so forth [14,15]. The majority of faults in shallow depths (< 200 m) are caused by fishing and anchoring while cable components contribute to a small portion of the total faults [16,17].

The result of the cable fault is the de-energising of a circuit. A short fault is the most common type [18, 19]. A short fault indicates that the cable has a break in the insulation between the seawater and the power feeding conductor, affecting the power supply between the two power stations [2, 18,20]. Above all, Insulation failure is the main result of cable faults, which depends on the electrical, mechanical, and thermal stresses in the submarine cable system. Determining the root cause of the failure can improve cable design and operation. However, it is very difficult to identify the mechanism underlying the failures. The insulation failure related to the electric, thermal, and mechanical stresses can be derived from complex physical and chemical processes, including cable ampacity, ambient temperature, type of backfill around direct buried cables or ducts, and the moisture or chemicals [19]. The insulation degradation and ageing by substantial water treeing at the fault sites are the key aspects of the insulation failure mechanisms [19,21]. Recently, a study of life and reliability of HVAC cable indicated that the load cycles affected by the soil temperature and thermal conductivity present a major effect on cable life [22]. The cable failure rate increases under heat waves, which is derived from the insulation degradation [22]. It is reported that the combined DC and high-frequency AC voltage produces the long vented water trees [23]. Interestingly, the tree growth increases with the AC voltage component [21]. Understanding the mechanism of cable failure and the new diagnosis method is beneficial to submarine cable development.

The aims of this study are described as follows: (1) Characteristics of HV submarine cables; (2) cable fault analysis; (3) discussion of cable failure mechanism; (4) key issues and prospects for the future development of submarine cables.

2 | HV SUBMARINE CABLES

2.1 | Submarine cables used in power transmission

Two main types of submarine power cables are typically used, including extruded polymeric cables [24, 25] and the self-contained fluid-filled (FF or low pressure oil filled (LPOF)) paper or oil-paper insulation [3, 24, 25]. In the latter case, mass-impregnate (MI) paper, which is impregnated with a low-viscosity polybutene compound oil, can be widely applied in HVDC submarine power transmission [9].

Table 1 shows the typical HV submarine cables and their applications [26–28]. Optical fibers are integrated into the cable for monitoring, such as cable temperature, cable strain, even for cable fault detection and the location [1]. Both MI and extruded polymeric cables with a three-core structure can be applied in HVAC power transmission. These submarine cables can support a high voltage of 500 kV and a large capacity of over 1000 MVA for offshore power transmission.

Figure 1 shows the evaluation of the power cable length of the submarine and underground cables [29]. From 2011 to 2017, the paper-insulated submarine cables could reach 3000 km. Since 1991, extruded polymeric underground cables have become incremental, and there has been an obvious increase in length since 2001. Hence, it can be inferred that extruded submarine cables have an optimistic future for offshore power transmission.

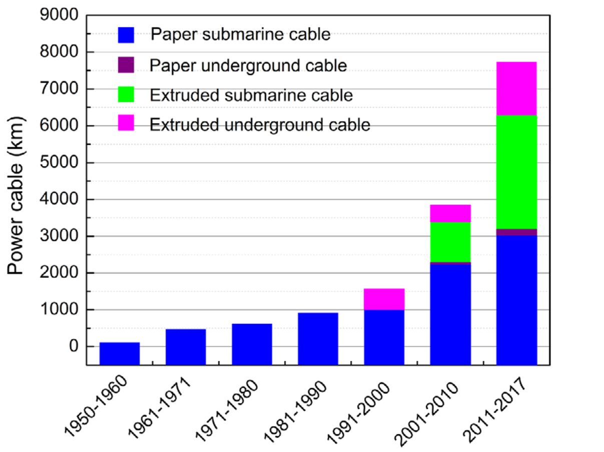


FIGURE 1 Used length of submarine and underground power cables (data from [29])

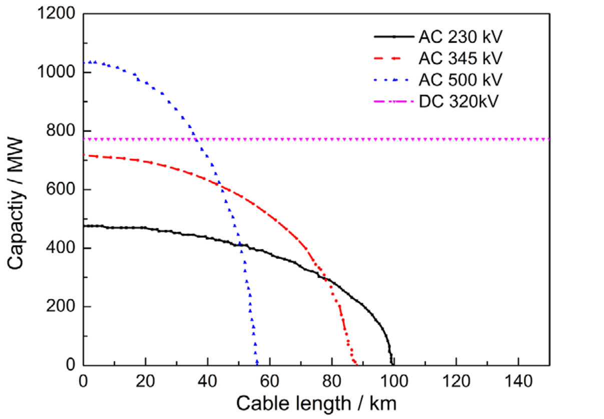


FIGURE 2 Transmission capacity as a function of cable length (data from [30])

It should be noted that the length of the HVAC submarine cable is less than 150 km due to the high loss and the required reactive compensation. Figure 2 shows the transmission capacity using different HVAC and HVDC power cables [30]. The capacity presents a substantial decrease with the length of the cable for HVAC transmission. When the cable length is greater than 50 km, the capacitance of the cable needs to conduct charging and discharging processes, which consumes most of the AC current. Usually, reactive power compensation is required, which can extend the transmission distance of HVAC. However, this increases the cost due to the applications of large amounts of reactive power compensation devices, such as a shunt reactor.

HVDC submarine cables can support long-distance offshore power transmission without the limit of a cable length (over 1500 km). The capacity can reach 800 MW using a 320 kV DC cable for over 100 km. The 450 kV MI cables with flat MI insulation with optical fiber can support 1270 km of HVDC transmission. Interestingly, the ±250 kV, 600 MW (bipolar) power cable with DC-XLPE insulation was designed by incorporating nanofillers. It is used for LCC-HVDC transmission due to the reduction of space charge accumulation in insulation. In the future, based on the major improvements for extruded cables, the operational range will be extended, such as the 550 kV HVDC submarine cable [29].

2.2 | Cable characteristics and working conditions

Extruded insulation cable, such as XLPE polymer, has few defects, high electric strength, and low dielectric losses. For example, the current can be reduced to 5.1 mA/m compared to 14.7 mA/m for 1000 mm^2 paper cables at 132 kV [31]. In a three-phase cable, a full screening from each phase conductor screen is assumed. For a coaxial-cable structure, the electric stress in the cable insulation can be given by

$$E(x) = \frac{U_{app}}{x \ln (r_0 / r_i)} \tag{1}$$

where U_{app} is the applied voltage; r_i is the conductor radius; r_0 is the sheath radius; x is the radial distance to any point in the insulation.

According to Equation (1), the maximum electric stress occurs on the surface of conductor. This position should be carefully designed for improving insulation degradation and lifetime. In general, an inner semiconducting layer is used for conducting electric field, and the static electric field radiates from its surface. If the defects exist near the surface of the conductor or internal semiconductor, the electric field distortion becomes more serious.

The minimum stress occurs at the external semiconductor, which presents a critical value for determining the insulation defect in the vicinity of the external semiconductor layer [24]. The typical maximum electric field (E_{max}) is almost approximately 10 kV/mm [8]. For instance, E_{max} can reach 17 kV/mm in the FF cable under extra-high voltage. It is 11 kV/mm in XLPE cable [24].

The relative permittivity for insulation paper and polymer dielectric is almost independent of the AC electric field and temperature. However, the DC conductivity presents a strong dependence on both the temperature and electric field [32]. The DC conductivity in the polymer dielectric can be described by the hopping model [32]:

$$\gamma(E, T) = A \exp\left(-\frac{E_a q}{k_B T}\right)\left(\frac{\sinh(B|E|)}{|E|}\right) \tag{2}$$

where A and B are constants of the material; E_a is the thermal activation energy in eV; q is the electron charge (1.602×10^{-19} C); k_B is the Boltzmann constant (1.38×10^{-23} J/K); T is the temperature in K; E is the electric field in V/m.

Figure 3 shows the calculated electric field distribution in the DC cable insulation. The temperature gradient occurs during a different simulated time. The electric field shows a high value at the inner semiconducting layer and a low value at the outer semiconducting layer. However, with the increase of the

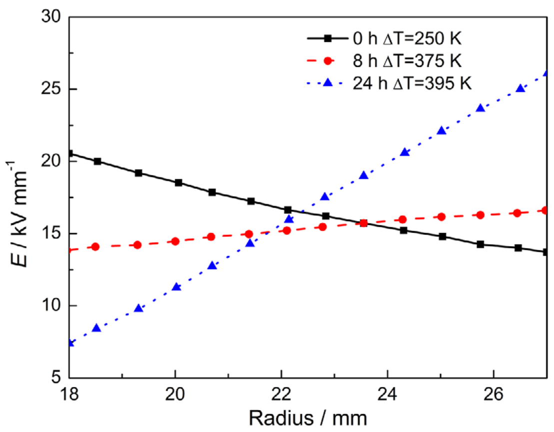


FIGURE 3 Relationship between electric field and thickness of cable insulation. The load current in the conductor is 3500 A (data from [32])

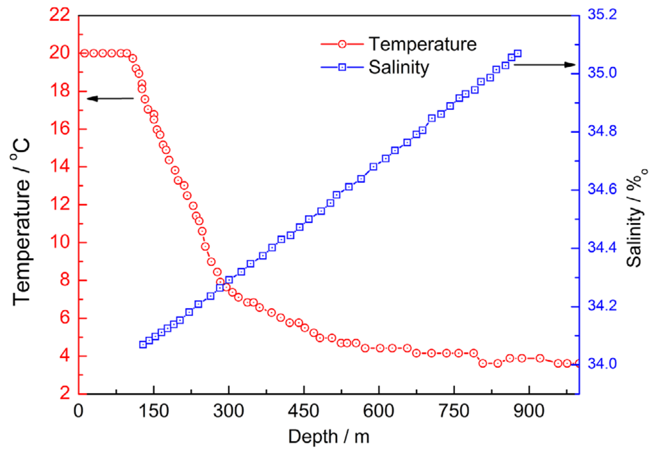


FIGURE 4 Temperature and salinity of the seawater, data from [3]

TABLE 2 Information on submarine cable burial depth [13]

Seabed	Burial depths/m
Exposed bedrock	0
Chalk	0–0.6
Stiff clay	0.4–0.8
Clay	0.6–1.2
Gravel	0.4–1.0
Coarse sand	0.4–1.0
Silty sand	0.6–1.2
Sand waves	0–3
Intertidal mudflats	0.6–3
Bench sand	1–2

temperature gradient (8 and 24 h), the electric field indicates an inversion in the insulation. It shows a substantial increase in the electric field at the outer semiconducting layer (28 kV/mm. This is mainly caused by the DC conductivity behaviour. As a result, space charge accumulation, breakdown, and degradation occur in HVDC submarine cable insulation [33].

The external condition is extremely important for the submarine cable application and lifetime. Submarine cables are usually buried under the seabed. Table 2 shows the typical burial depths under different seabed types [13]. The cable burial depth depends on the type of habitat, the sediment of the seabed, and the water depth. In general, a standard burial depth of 1.8 m is mentioned. Under heavy ship traffic, the burial depth is proposed to be larger than 3 m. The offshore wind farms require the cable burial depth to be at least 0.6 m. The submarine cables suffer from temperature, pressure, and corrosion due to the burial conditions [1, 2, 34].

Generally, the submarine cables are laid in shallow water of less than 500 m. The hydrostatic pressure exerted by the water affects the cable laying, operation and repair. The water pressure increases linearly with depth at each 10 m steps [3]. Although the submarine cable sheath is designed to resist high mechanical stress, some manufacturing segments for protecting the cables should be considered in deep water. Some defects and small cracks appear due to the high tensile forces. The special design for materials in the MI and XLPE cables, such as the high-density and high-viscosity compounds, can respond better to the mechanical force.

Temperature and saltwater have a great influence on the submarine cable installation and operation. Seawater temperature generally drops with water depth. It can reach 4°C at a 1 km depth, keeping this low value down to the sea bottom [3] as shown in Figure 4. If the burial depth is large enough, the heating by a large conductor current could degrade the cable insulation because of the low thermal conductivity of the insulation layer. Figure 4 shows the salinity of seawater with an increase in depth. The salinity usually increases with depth, which presents a complex movement related to water density, heat accumulation, and temperature. The average salinity in the ocean is approximately 33–36‰ with large variations. The corrosive effects of the salty water can damage the cable armour, sheath, and even insulation. The zinc and steel armour and high-density polyethylene as an insulation sheath is useful for protecting the cable from the corrosive nature of salty water. The burial cable in the seabed reduces the influence of salty water.

3 | FAILURE OF SUBMARINE CABLES

Based on the fault data from the Submarine Cable Improvement Group [16, 35]. External aggression includes fishing, anchors, abrasion, geological, dredges, crushing and others is the dominant category. Figure 5 shows the fault data statistics for external aggression. Human activity, such as fishing and anchors, has proportions of approximately 67% to 72% from 2004 to 2009. Fishing or dropping and/or dragging anchors remain the major cause of external aggression. The reduction in fishing faults after 2010 is probably attributed to the law prohibiting fishing. It indicates that the shore-end surf zone abrasion can cause a higher abrasion fault rate. This is an important factor in planning and protecting cables. There have still been some faults caused by other/unknown reasons (~10%).

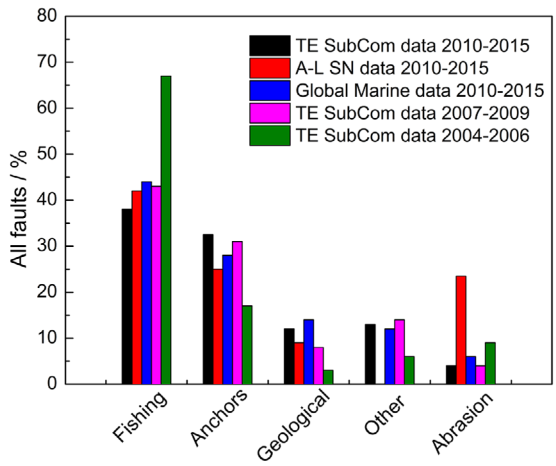


FIGURE 5 Fault statistics of submarine cable system for external aggression (data from [16, 35])

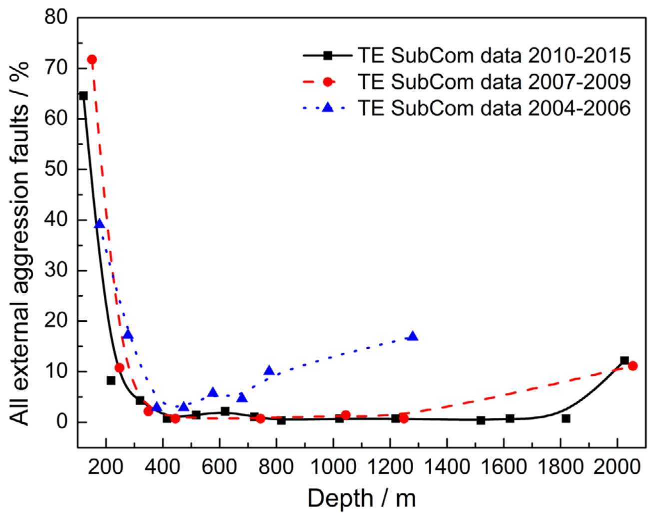


FIGURE 6 Relationship between the external aggression faults and the depths (data from [16, 35])

Figure 6 shows the depth distribution of external aggression faults. It indicates that most of the faults occur in water depths of 300 m or less. Only approximately 20% of faults occur at depths greater than 1000 m. It should be noted that new power cables have been deeply buried in the last six years, leading to a reduction in faults, especially for cables at depths of less than 200 m. However, they are still 10% faults around 2000 m.

According to the statistical analysis of Conseil International Des Grands Reseaux Elecctriques (CIGRE) and other reports [17,20], the failure rate is used to analyse the cable fault, which is defined as

$$F_{\mathrm{r}} = \frac{\sum_{i=1}^{n} N_i}{\sum_{i=1}^{n} A_i} g100 \qquad (3)$$

where N_i is the number of faults in the cable components during the ith year of the period of concern. A_i is the number of cables in service at the end of the ith year (km). F_r is the failure rate that presents the number of faults per 100 km per year.

External faults, such as mechanical damage by anchoring with the rapid breakdown or an unplanned outage of the cable system are the main types of failure. Much attention should be given to mechanical protection against third-party damage, especially for directly buried cables [20]. The failures caused by anchor and trawling are considered to be instantaneous. Buried submarine cables can effectively resist fishing gear, but it is difficult to exclude damage by anchors. Heavy anchor (30 T) can penetrate more than 5 m if the soil is not too hard [20]. Besides, heavy fishing gear can penetrate less than 0.5 m in the soft soil [20]. A relatively high percentage (33%) of faults are reported but are caused by 'other/unknown' reasons [17]. It is necessary to study these complicated faults further.

Cable joints and terminations are designed with a special complicated structure with multilayer insulation [5], which are important parts of the cable system. Some defects may generate on the XLPE cable joints due to the cable preparation, such as peeling tools, polishing techniques, and interface treatments. It can threaten the operation of the cable joint.

There are still insufficient data to quantify a fault rate for cable accessories. It is accepted that cable joints and terminations exhibit weak points for breakdown and degradation. The electric and thermal stresses probably happen, causing thermal and electrical failure. Much attention should be given to the design, material characteristics, and electric and thermal stresses in cable joints or terminations, especially for HVDC applications.

4 | FAILURE ANALYSIS AND DISCUSSION

4.1 | Types of failure and analysis

The majority of the submarine cable failures are derived from the insulation degradation and breakdown, which originated from the thermal, electric, and mechanical stresses in the cable configuration. As a result, a short fault occurs between the seawater and the power feeding conductor.

It indicated that arcing usually occurs in the conduction path, resulting in overheating, degradation, and ageing of the insulation, forming a short-circuit failure [19]. Short-circuit failures give rise to the action of the protection device and cut the current flow to the load. However, if the protection device fails to switch off, the flashover exhibits continuous development causing serious consequences, such as a thermal breakdown.

Compared to the conductor core, the optical fiber has a small size, lightweight, and low electric strength. It is reported that the optical fiber probably behaves as a weak point in the cable system [36]. For example, the failure analysis report of one offshore wind farm submarine cable in the United Kingdom indicated that the breaking of optical fiber caused cable failure (short fault) [36]. This fault cable is a type of three-core submarine XLPE cable of 132 kV, connecting the offshore wind farm to the power grid on land. It is recognised that the optical fiber is exposed in the magnetic field with a 50 Hz AC current in the conductors. The induced current and voltage can be formed in the outer metal sheath of the optical fiber. If the magnetic field substantially increases by the rapid transient effect, the induced current increases leading to power loss and heating.

AC current can generate an alternating magnetic field, causing a weak induced electric field of μV m^{-1} [37]. When the conductor current and cable distance increase, the electromagnetic fields increase [38]. A magnetic field of approximately 3200 μT is formed in a submarine cable with a 1600 A conductor [39]. When using the seawater as electrodes for the current return in the mono-polar DC power transmission, a higher induced magnetic and electric field can be formed [40]. The generation of these electromagnetic fields and the related effects can increase the power losses and heating of the cable, which affects the cable operation and safety. In other cases, some marine species can detect the electromagnetic fields, resulting in a few incidents of cable damage by bites [41].

To determine the root cause of the failure analysis, the cable itself, the operating conditions, the design, and the laying should be considered. First, various measurements of the damaged cable and the nearby pieces are very necessary. The analysis of the cause/effect loop can contribute to the fundamental or root cause. The failure reasons can be derived from the mechanical force, thermal runaway electric stress, and combined effects. Next, it is necessary to study the failure mechanism. Failure modelling using the microcosmic and macroscopic electric and thermal theory and analysis of the material parameters are of great importance for obtaining the root causes.

4.2 | Discussions of the failure mechanism

4.2.1 | Overvoltage and electromagnetic transient

In submarine cables, the armour can be assumed to be the ground potential and present a wet construction to allow the seawater to penetrate the armour. Metallic sheaths are usually grounded at both cable ends. It is accepted that the cable transient voltage with high frequency can propagate as decoupled coaxial waves between cores and sheaths [42]. The velocity, attenuation, and surge impedance can be affected by this transient voltage depending on the core modelling, insulation material, semiconducting material and metallic sheath [43]. If the insulation loss increases, the transient voltage indicates a strong attenuation and narrow pulses [44]. This transient voltage can reduce the stability of power transmission, even causing cable failure. In the case of the grounding fault condition, a large zero-sequence current at the power frequency flows in the conductors outside the sheaths (armour, pipe) due to the unshielded sheath from the magnetic flux [45]. This leads to an increase in the fault current.

Figure 7 shows the overvoltage waveform of the XLPE submarine cable with 5 mm steel-wire armour, 15 mm outer insulation, a 2 mm lead sheath, and 1 mm semiconducting screens [43]. A high ratio of over 1.6 can be reached at the beginning of overvoltage. If the transient high voltage frequently occurs, some partial discharges probably happen at the positions where impurities and defects exist. Besides, this high voltage with a

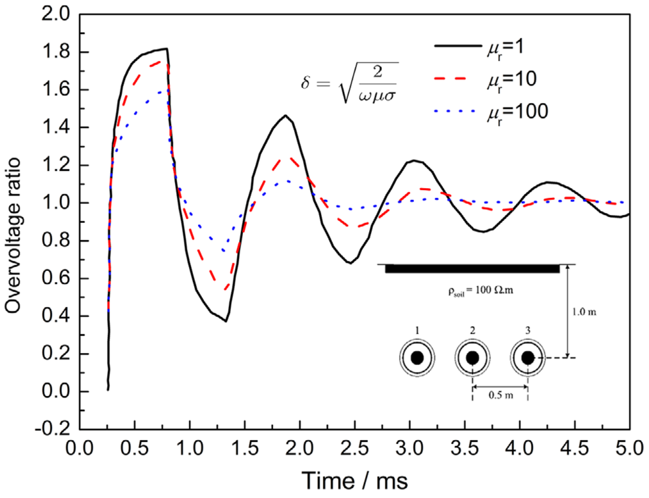


FIGURE 7 Overvoltage waveforms under different armour permeability (data from [43])

high frequency can increase the dielectric loss of the insulating material. During the long-term operation, the dielectric hearing would increase. Hence, cable degradation would occur.

The conductor and the lead sheath voltage waveforms of a 250 kV DC oil-filled submarine cable show a surge increase voltage of less than 0.5 ms [46]. The voltage peak exhibited a reduction with the length of the cable, causing the inhomogeneous distribution of the electric field. The non-uniform charge accumulation at the insulation interfaces would cause the local high-electric field due to the minor defects, cracks split and pollution.

4.2.2 | Partial discharge (PD)

Due to the manufacturing defects, contamination, and cable insulation degradation, partial discharges (PDs) are likely to occur in the voids or at protrusions inside the insulation layer and surface/interface areas [24]. Besides, the harmonic voltages with pulse peaks in HVDC submarine power cables are introduced [44], which will cause the PDs in the insulation. The charge density is much higher on the surface of the void by PDs [47]. The charge density on the electrode surfaces increases with PD development causing the electric field distortion near the void surface. This can affect PD behaviours in return. The insulation becomes degraded because of the subsequent PDs. The void enlargement can be formed by the energetic electrons bombarding the cavity and chemical reactions by sustained discharge by-products, including ozone and acidic products [24]. Two substantial results can be formed by PDs. One is the direct insulation degradation and ageing caused by discharge damage [46]. Another is the corrosion and heating from the chemical products by PD effects [46, 48].

It is reported that PDs occurred in the shrinkage cavities of MI insulation. The void could expand and extend axially between the insulating paper layers. Consequently, PDs developed, forming the discharge channels and resulting in insulation

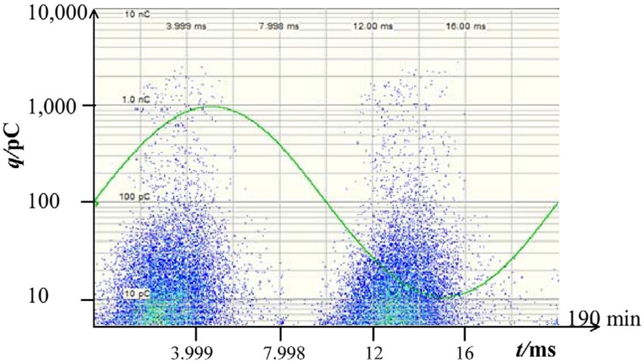


FIGURE 8 PD plots under 70 kV of the cable [52]

breakdown. It turns out that the carbonised channels caused by PDs could extend 1 m along the cable axis [49, 50]. This failure due to PDs is called a load-cycling breakdown [51].

Figure 8 shows the PD patterns after the rated load current turn-off [52]. PDs occurred and reached the maximum during 1–3 cooling. This indicated a result of shrinkage void formation. After that, more strong PDs occurred, and the number of charges could reach 1 nC at 190 min. These powerful PDs appeared for a few hours during the cooling period. At that time, the load cycling breakdowns were produced during the measurements. However, the influencing factors, such as pressure gradient and load change on dielectric characteristics of shrinkage void, are not clear for PD development.

The measurements, such as PD patterns and time domain reflectometry (PD localisation), are useful for detecting the defects in the insulation and accessories of HV power cables [53]. The use of damped AC voltages is a useful measurement for long cable tests of offshore wind farm submarine cables [54, 55]. PD activities are closely related to cable degradation and ageing. Usually, it is difficult to detect PDs for submarine cables. It is useful to extract the typical PD signals from the faulted cables for studying the PD mechanism.

4.2.3 | Electrical and water treeing

Electrical trees are the 'treeing' like phenomena in polymer insulation, which are caused by the local high electric field. The electrical tree is induced by the inside void, protrusions, and contaminants that are similar to the PDs. The difference is that the electrical tree has a branched structure with large discharge channels growing along the electric field lines. Usually, the discharge channels of the electrical tree can reach several tens of micrometres with diameters of 1–20 μm [24]. Unlike the PDs, the propagation of an electrical tree is difficult to stop if it occurs inside the insulation. Moreover, treeing phenomena are the most important reason for the mechanism of cable failure.

Electrical tree depends on the material, voltage, space charge, temperature, and so forth. For example, the electrical tree under DC voltage presents voltage polarity effects [56, 57]. The electrical tree under the AC voltage exhibits more branched structures, while it presents more bushed trees under DC voltage. In HVDC power transmission, a rapid increase in the AC voltage can be superimposed on the DC voltage to change the electrical tree characteristics. Figure 9 shows the typical electrical growth under the combined AC and DC voltage of XLPE cable insulation (160 kV HVDC cable) [58]. Under the AC voltage (15 kV), all of the electrical trees are pine-like structures, and more branches are produced with time. It should be noted that the pine-like trees in this situation are closely related to the negative charge injection and accumulation near the needle electrode. At the first step of tree growth, the PD activities are weak. With the increase in the electrical tree, the PDs become large. The increase in PDs can contribute to electrical tree growth in return. The propagation rate of the electrical trees increases with the increase in the AC voltage. In the case of positive DC voltage, the electrical tree growth increases rapidly compared to that of negative DC voltage [58].

Space charge inside the insulation is a key factor for tree growth. In the case of a short tree, there are large amounts of charges around the tree tip, forming the charge boundary. Due to the trapping and detrapping processes of the charge transport model, the energy release would break the molecular chains, resulting in the low-density region. The trees can develop more quickly in the low-density region forming a rapidly increasing stage of treeing [59]. In the case of long tree growth, the trapped charges around the tree tip are small restricting the growth of the trees by the weak discharges. The growth of the trees becomes slow, and a stable situation is maintained. The trees develop continuously by the increase of space charge in the local high field area [59].

In addition to electrical trees, the presence of water is the key factor in producing the water trees inside the insulation. The water treeing phenomena depend on voltage, frequency, temperature, and moisture [60]. Compared with the electrical trees, water trees present different structures and growth characteristics. The similarities are that the water trees initially start from the defects in which a high electric field is exhibited accompanied by discharges, chemical products, and breakdown channels. In general, two types of water trees usually occur in submarine cables. One is large vented trees, which originate from the insulation surface or semiconducting layer as shown in Figure 10(a). Another is bow-tie trees, which are derived from contaminants or voids in the semiconducting layer as shown in Figure 10(b). Interestingly, the electrical trees can develop at the tip of the water tree, especially for the bow-tie type of water trees. The laid circumstances of the XLPE cable and the occurrence probability of the voids and impurities determine the water tree degradation. The growth of water trees is much slower than that of electrical trees. It may need several years for treeing development. The eventual failure caused by the water trees seems difficult to occur for low voltage cables. However, in the case of HV submarine cables, water treeing plays a dominant role in cable ageing and degradation failure [23, 61].

It has been found that water tree growth is slow under a high DC voltage in comparison with AC voltage [23]. Generally, water treeing under DC voltage is difficult to produce. However, for HVDC power transmission, water treeing induced by combined DC and high-frequency AC voltages increases.

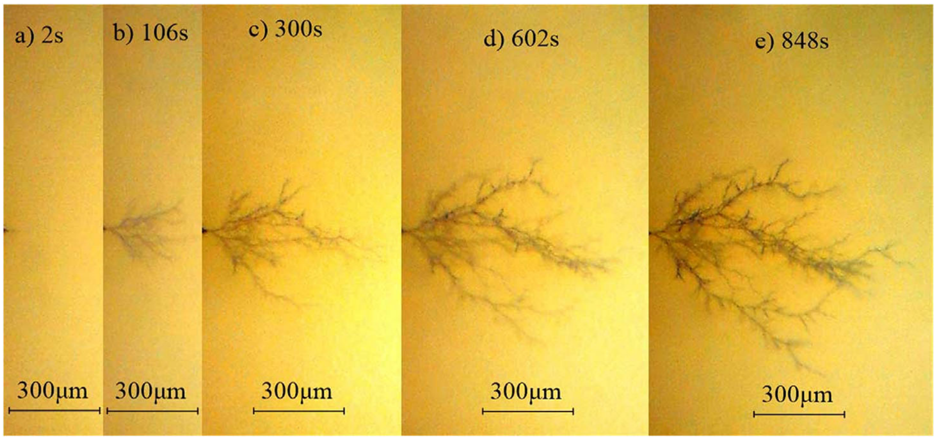
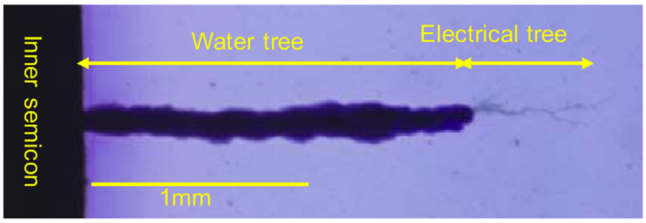
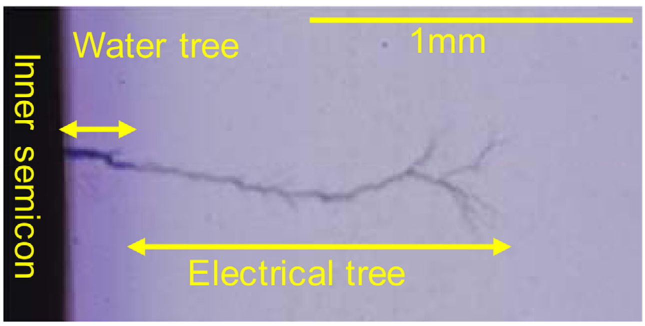


FIGURE 9 Dynamics of electrical tree growth under 15 kV AC with -30 kV DC voltage [58]



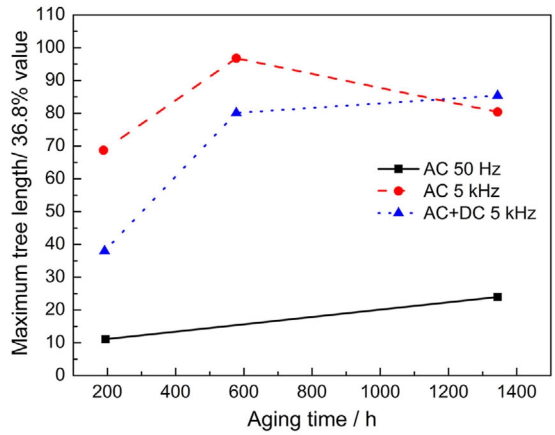
(a) Vented water tree and electrical tree development



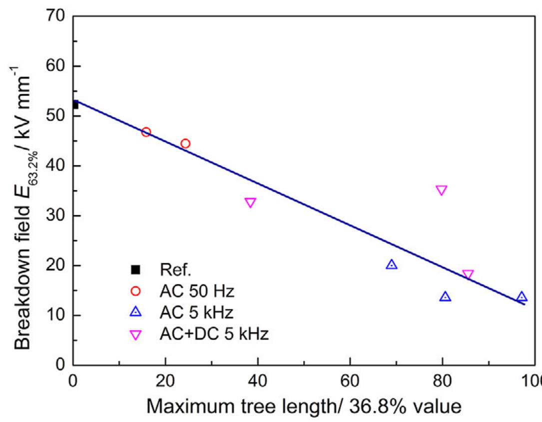
(b) Bow-tie type of water tree and large electrical tree

FIGURE 10 Types of water trees and developments in XLPE cable insulation [62]. (a) Vented water tree and electrical tree development, (b) bow-tie type of water tree and large electrical tree

Figure 11(a) shows the water tree growth length under different voltages. All the tree lengths increase with ageing time. A small value (less than 30) is presented under AC power frequency voltage, while it shows an obvious increase under the AC 5 kHz and combined AC and DC voltages. It is said that the increased trees by the combined DC and high-frequency AC stress result in no zero-crossings. The space charge accumulation occurs near the tip of the vented water tree where the electric conductivity is high. The space charge increases due to the interfacial polarisation caused by the difference of conductivity of the treed and non-treed regions. The charge injection and extraction would occur at the tip of the tree structure, which depends on the voltage frequency. When the high-frequency AC voltage is applied, the number of zero-crossings increase, leading to an increase in the charge injection and space charge accumulation. As a result, the water tree increases.



(a) Tree lengths from the lower electrode



(b) Breakdown stress with the tree length

FIGURE 11 Relationship between water tree and breakdown stress of XLPE insulation, data from [23]. (a) Tree lengths from the lower electrode, (b) breakdown stress with the tree length

Figure 11(b) shows the breakdown stress with the water tree lengths under different voltages [23]. A long water tree length leads to a low breakdown strength. A breakdown strength of approximately 10 kV/mm can be obtained as bridging water trees [30]. It should be noted that electrical trees and local

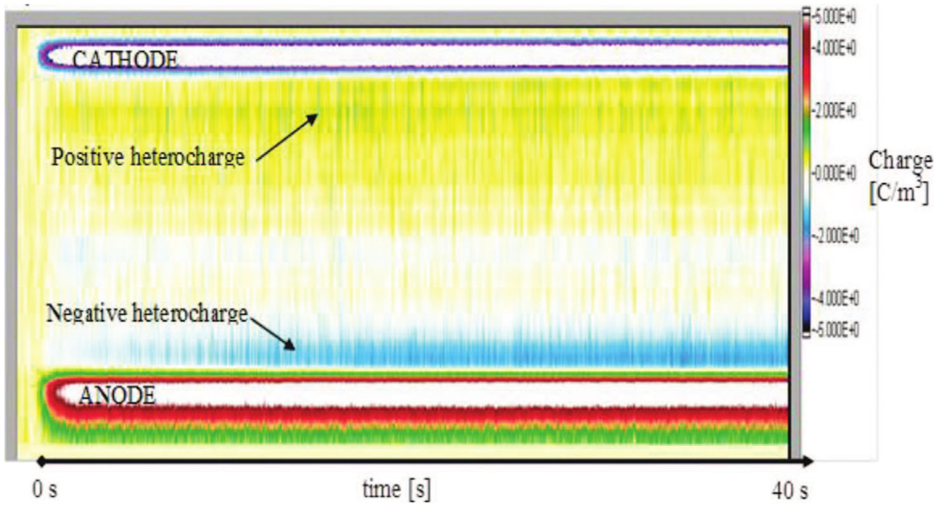


FIGURE 12 Space charge distribution of XLPE mini cables at 40 kV/mm and 70°C [71]

breakdown points occurred at the tip and in front of long vented water trees [23]. Electrical trees can grow into the water trees resulting in the extended breakdown channels. Space charge is found to be a key reason for the water treeing and insulation breakdown.

4.2.4 | Space charge

Space charge is considered a root reason for cable failure underlying the PDs, treeing, and breakdown mechanisms [12]. Polymer insulating materials in power cables have complex morphology structures, such as an amorphous region, a crystalline region, cross-linking, free volume, and chemical radicals. These can generate some physical and chemical traps inside the materials [63,64]. The traps and defects are regarded as the sources for space charge accumulation. Besides, the charge injection from electrodes and the trapped controlled charge transport inside the insulation contribute to the complicated space charges. For examples, the space charge limited current [65] and charge packets [66, 67] under high electric fields were formed. Space charge can generate inside the cable insulation under high fields and temperatures, as well as at the interfaces in the cable joints under low electric fields.

Space charge characteristics are mostly affected by voltage types, temperature, moisture and radiation [12, 68, 69]. It is accepted that the space charge accumulation under DC voltages is usually larger than that of AC voltages. In general, the charge accumulations happen at the interfaces between the insulation and electrodes under AC voltages due to the polarity reversal, while bulk space charges exist under DC voltages. The increase in the temperature and moisture can promote the charge injection and accumulation causing the local field enhancement and high conduction current. In HVDC power transmission, space charge is regarded as a key fundamental issue in the design and application of submarine cables and joints [70].

An interesting fast space charge pulse was found in a full-size cable (conductor diameter = 2.8 mm, inner semicon thickness = 0.7 mm, dielectric thickness = 1.5 mm, outer semicon thickness = 0.15 mm), which can threaten the power cable insulation [71]. Figure 12 shows the space charge pattern during the 40 s of XLPE cable insulation. Heterocharges occur immediately under the voltage application and migrate towards the opposite electrode. The charge pulses move quickly (50–300 ms). The mobility of the charge pulses is evaluated as 10^{-10} $m^2\ V^{-1}\ s^{-1}$, the repetition rate of the charge pulses is approximately 1 to 3 s^{-1}. Fast charge pulse was measured and analysed due to the threat to HVDC cable insulation. It indicated that the fast mobility of these pulse charges contributes to the high electric conduction in the insulation, which decreases the insulation resistivity and enhances the current. Consequently, cable degradation would occur. Moreover, the fast pulse charges are from the rapid accumulation of heterocharges. The lifetime estimation considering the electric field by heterocharges indicated a life reduction due to an extra field. It can be concluded that the reliability of DC cable insulation is affected by the effects of pulse charges. It is deduced that the increase in the energy state in polymers could respond to the fast charge pulses in the cable insulation [71]. Chemical–physical characteristics of the polymer insulation should be considered for cable design in the future.

Another high probability for the cable joint failure is the insulation breakdown caused by space charge effects. This high electric stress becomes serious in the cable accessories due to the interface charge accumulation. The breakdown path under the DC condition starts at the cable/accessory interface where multilayered insulation is used. In the XLPE cables, cross-linking by-products are normally present leading to the space charge accumulations [72]. The by-products at the interfaces produce more traps and defects enhancing the space charge effects in the cable joint. Careful consideration should be carried out for the design of cable joints and accessories. It is reported that accessories with ethylene-propylene rubber components present few space charges at the interfaces and have good prospects for application of the above 320 kV HVDC extruded submarine cables [73].

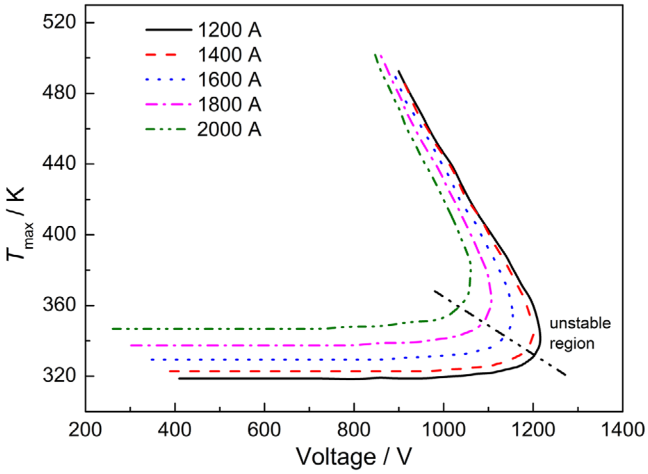


FIGURE 13 The maximum insulation temperature versus applied voltage at different load currents (data from [74])

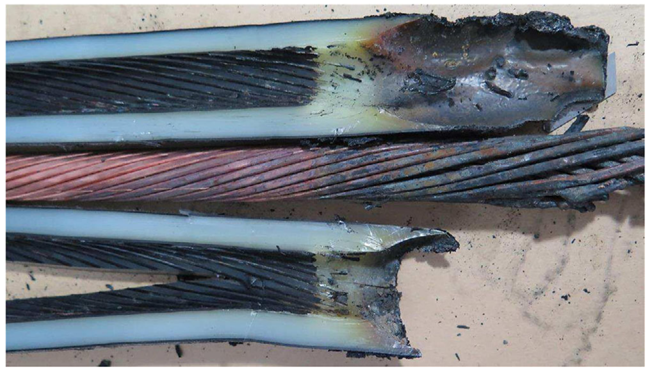


FIGURE 14 The breakdown of the 35 kV submarine cable. Significant burning and arcing occurred in the conductor and insulation

4.2.5 | Electric-thermal degradation

Under normal conditions, the electric field and temperature have critical values for cable application. When the stresses exceed the critical values, the cable degrades. The local field distortion and thermal instability can give rise to the PDs, treeing, space charge, and breakdown failure.

Figure 13 shows the maximum temperature of cable insulation concerning the voltage and current. A nearly linear relation between temperature and voltage can be obtained in a stable region. A high temperature can be obtained with the increase of current. Interestingly, a thermal instability region can be observed after the critical values of voltage and temperature. This area is particularly important for cable degradation. The estimated critical temperature is lower than the decomposition temperature of XLPE cable insulation, and it is difficult to directly cause the breakdown. Hence, it is critically important to consider the region between the stable and unstable areas where thermoelectric degradation (electro thermal runaway) of the cable could easily occur. The maximum stable temperature can affect the insulation breakdown [74]. Similar analysis thermal analysis and runaway are considered in the cable joint [75].

Power loss is a key factor to affect the thermoelectric characteristics of submarine cable. The high values of conductor loss, lead sheath, and armour losses can be evaluated by the International Electrotechnical Commission (IEC) standard and the published work [76, 77]. Recently, it has been shown that power loss evaluation by the finite element method (FEM) can be used to improve the accuracy of the IEC calculations [78, 79]. For example, the sheath losses can be accurately estimated by considering the proximity effects, including the eddy current loss [79]. In addition, the geometric factor G is improved to calculate the thermal stress [80]. The above power loss calculations are beneficial for revealing the thermoelectric stresses in submarine cables.

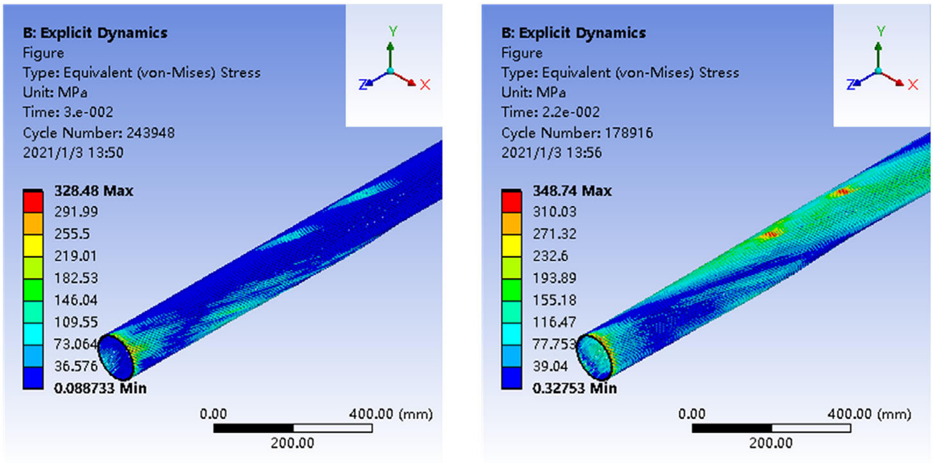
Figure 14 shows the picture of the broken cable conductor and insulation in a three-core faulted submarine cable. An obvious burning and arcing on the surface of the semiconducting layer, the conductor and insulation interfaces are found. This failure is caused by the electric-thermal degradation that probably starts from the cable outside. Initially, the jacket is damaged resulting in the water permeating into the cable. Serious corrosion of the metallic shield is subsequently formed. With the developments of surface tracking and flashover, the thermal concentration and field stress become sustained and increase, leading to the enhancements of power loss. Consequently, PDs, treeing, heating, and local breakdown would occur. It is emphasised that the mechanism underlying the thermoelectric failure is the integrated effects of the above phenomena.

4.2.6 | Mechanical degradation

In general, it is difficult for external damage to cause the direct breakage of the cable due to the high-strength armour. Commonly, fishing and anchoring change the strain and stress of the cable material, such as the armour, metallic sheath, semiconducting layer, insulation and optical fiber. Then, some cracks, voids, and deformation can be formed leading to defects on the cable surface and inside the cable. The electric and thermal stress concentrations occur at the local defect positions. Moreover, the moisture and impurities can permeate the cable causing the thermal-electric degradation of the cable. Usually, it takes a long time for cable failure. However, sometimes cable failure develops quickly when serious mechanical damage from anchoring occurs or in the presence of a high transient overvoltage.

It is reported that cracks and extensive voids can be produced in the cable insulation from complex mechanical stresses [19]. Hence, the cracks of the insulation then extend due to the overheating and electric stresses. The increase in the conductor ampacity, local thermal runaway and flashover cause the overheating of cable leading to the cable failure. According to the analysis of the mechanical force of the submarine cable under deep water, the increased pressure combined with the external force will cause the formation of the voids. Such extensive voids are not yet clearly understood.

The cable structure of an optical fiber unit is easily broken by the impact force from anchoring [81, 73]. The flexural deflection and local indentation are formed in the cable structure [81, 82]. Figure 15 shows the results of FEM of the cable armour



(a) 10ms (b) 30ms

FIGURE 15 Simulation of armour deformation of a 35 kV three-core submarine cable. (a) 10 ms, (b) 30 ms

considering the impact damage by anchoring. Cable armour deformation at the anchoring position is obvious. The large impact force can cause armour deformation, which depends on the falling height and weight of the armour, and the mechanical degradation of the cable structure occurs, including the armour, sheath, semiconducting layers, insulation and optical fiber.

It should be noted that the material parameters, especially for polymeric materials with non-linear elastic-plastic behaviour, play key roles in the cable deformation. The damage to the internal cable depends on the displacement rate of the armour. However, the cause of the damage is still not clear for the optical unit and insulation damage processes. It turns out that some of the submarine cables maintain the insulation when anchoring. However, the internal cable degraded. Consequently, PDs, treeing, heating, and local breakdown probably occur, causing the eventual cable failure.

5 | KEY ISSUES AND THE PROSPECT OF SUBMARINE CABLE FAILURE ANALYSIS

5.1 | Anchoring damage characteristics and mechanism

The key issues associated with the anchoring and the underlying mechanism are described below:

1. Examine the environmental condition concerning the anchoring, such as the water depth, burial depth, temperature, weight and dynamics of anchor movement.
2. Construct the experimental platform for cable anchoring. It is very difficult to simulate the submarine cable conditions. Experiments considering anchoring should be studied in the future on the land.
3. Deeply understand the mechanism caused by anchoring. It is important to investigate the influence of material parameters, such as the non-linear elastic-plastic behaviour on cable deformation. Furthermore, the relationship between the deformation and the thermal-electric failure should be considered.

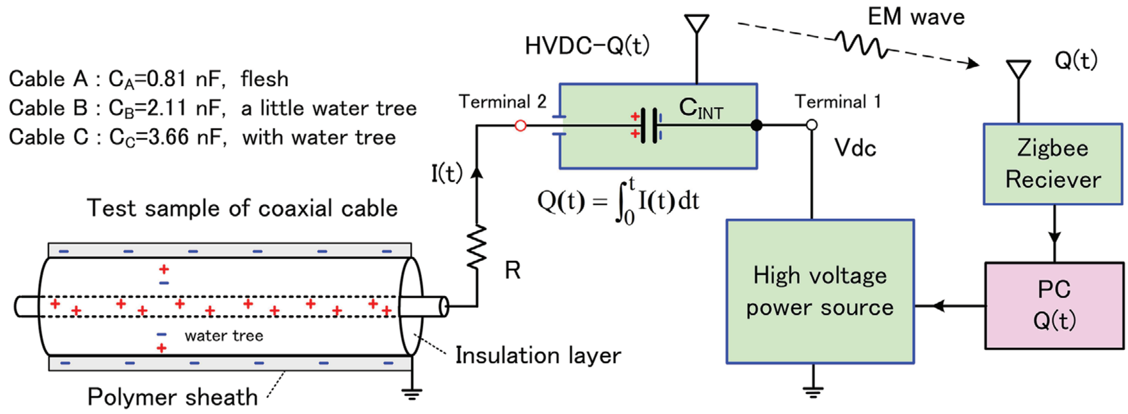
Recently, the dynamic characteristics of a tunnel structure were used to protect submarine cables [83]. The simulation methods, such as the element-based finite-volume method with ANSYS-CFX software can be used to damage the assessment of anchor collisions [83]. The equivalent experiments of the cable collision considering tunnel-type structure are useful to validate the simulations. It is suggested that the increase of thickness of the upper layer of the tunnel structure can reduce the impact force [83].

Another method for protecting the submarine cable from the anchoring is the burial depth. In general, the increase of burial depth can reduce the mechanical damage for submarine cable. However, the deep burial presents a high cost and causes the temperature rise and corrosion from the seabed. It is accepted that the burial depth varies over time by movements of sand and the submarine cables themselves [84]. Monitoring the changes in burial depth is useful for cable protection and early warning. Except for the high-cost method (submarine robots), new methods, such as distributed temperature sensing, electric load data and thermal models are beneficial to the real-time determination of the cable depth [84].

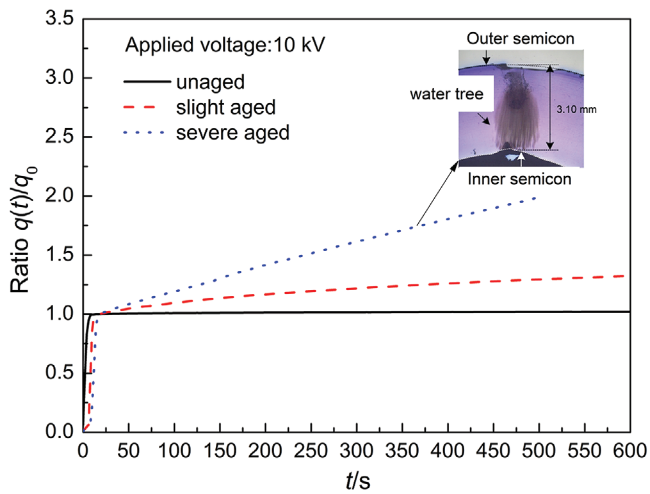
5.2 | Electrical and water treeing degradation

The treeing mechanism, the evaluation and the lifetime model of the submarine cable considering treeing is still not clear. The following issues and prospects should be focused on:

1. The origin of the electrical tree and water tree with the water barrier layer should be considered.
2. The influence of the space charge on the electrical tree and water tree behaviours should be considered. Not only the accumulated charges but also the rapid migration charges could contribute to the treeing.



(a) Schematic of the DCIC-q (t) measurement for water tree aged cables



(b) q(t) ratio of XLPE cables subjected to the different water treeing aging under 10 kV

FIGURE 16 Direct current integrated charge (DCIC-q(t)) method and the evaluation of water tree aged XLPE cables. Data from [88]. (a) Schematic of the DCIC-$q(t)$ measurement for water tree aged cables, (b) $q(t)$ ratio of XLPE cables subjected to the different water treeing ageing under 10 kV

Some new methods are required to improve the treeing degradation in the submarine cable. For example, the nanocomposites incorporating reinforced nanofillers into XLPE insulation can reduce water tree growth [85]. It indicated that the layered silicate/XLPE nanocomposites exhibit a large interfacial region between nanoclay and XLPE polymer matrix, resulting in a strong interface interaction. This high stress of the interface can prevent water tree growth [85]. Future works should be studied deeply on the morphology and modification of nanocomposites, and the underlying mechanism for treeing restriction.

It is found that the addition of amphiphilic surfactants into the cable insulation can suppress the water tree initiation, especially for the bow-tie trees [86]. Molecular dynamic simulation and quantum chemical calculation indicated that a reverse micelle was formed by the interactions between the surfactants and water molecules [86]. The spread of the reverse micelle depended on the van der Waals, electrostatic, and hydrogen bonds inhibited the water tree initiation [86]. Some further works should be considered on the experiments and material design.

The suppression methods and mechanism of electrical trees in the submarine cable depend on the structure-property and microscale characteristics of cable insulation material. It is suggested that the initiation of an electrical tree is determined by the Maxwell electromechanical stress, charge injection-extraction, charge trapping, and electroluminescence [87]. The advanced methods such as new organic additives (antioxidants and absorbers) with macromolecules and inorganic nanofillers with surface functionalisation were proposed for future studies [87].

The diagnosis and evaluation of submarine cable degradation by water trees are of significance to future cable development and application. Recently, we proposed a new method-direct current integrated charge (DCIC-$q(t)$) technique to detect and analyse the water tree aged cable [88]. Figure 16 shows the typical DCIC-q(t) measurement principle and the charge ratio results during DC voltage for different aged cables. The

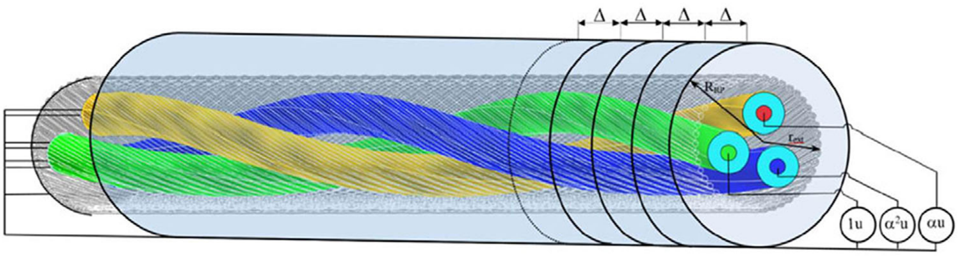


FIGURE 17 Three-core submarine cable inside a common return path with an indication of Δ-long elementary cells and two different lay lengths β,γ [89]

measured charges presented an increase with time under 10 kV for the aged cables. While the unaged cable shows little change of charges during the measurement. The charge ratio under different voltages is much higher than 1 for the severely aged cable [88]. It indicates that large amounts of charge injection and accumulation were produced in the severely aged cable. That is mainly caused by the ionisation, defects, and decomposition of local XLPE insulation by water treeing. Hence, this new method is useful to diagnosis the state of ageing in a submarine cable by the charge accumulation characteristics.

5.3 | Electric-thermal degradation

The electric field and power losses can be regarded as the sources for the discharges and heating.

1. Modelling of thermal-electric stresses of submarine cables considering the coupling effects. It should contain material parameters (dynamics, non-linear), calculation methods, and environmental factors (temperature, moisture, salinity etc.).
2. An improved thermal-electric ageing model should be considered. It is emphasised that the multifactor ageing related to space charge, treeing, overvoltage, and heating would be useful to understand the ageing.
3. The thermal-electric degradation failure should be predicted in terms of the data from the optical fiber. Combined with the ageing model and an intelligent algorithm, it is important to provide suggestions for cable operation and maintenance.

Simulation of electric, magnetic and thermal fields in submarine cables play an important role in the thermal-electric degradation characteristics. Recently, a new method of multiconductor cell analysis was proposed and applied to a three-core submarine armoured cable, which can calculate the cable impedance, power loss and current density [89, 90]. It can significantly reduce the central processing unit (CPU) times compared with a commercial FEM software, such as FLUX 3D [89]. Figure 17 shows a three-core submarine model with a very thick subdivision with circular subconductors. The element cell length Δ of different subconductors was used for the calculation of self and mutual impedances, which can be chosen freely. Both bonded active and passive conductors are earthed at the receiving end. The return path radius R_{RP} was selected as 10 times the external cable diameter [89]. Choosing the total number of subconductors can give rise to very high precision with lower computational time. The calculation of the power loss considering the screen loss factor indicated a high level of agreement with the FEM commercial software within a short time [70]. This computation can be regarded as a new method to rapidly analyse the submarine cable transmission and electrothermal property in future cable design, operation and fault analysis.

Evaluation of the life and reliability of the submarine cable considering the time-varying electrothermal fields is of great importance to the cable failure analysis and application. A case study approach was adopted to assess the life and reliability of an HVAC XLPE insulation cable by introducing the seasonal factors [22]. $LF_{j,k}$ was defined as the fraction of life lost by cable insulation during the jth step of each daily load cycle of the kth season. Then, the cable life can be estimated [22]:

$$LF_{j,k} = \int_{0}^{\Delta t_{j,k}} \frac{dt}{L\left[E\left(r_i\right), T_{j,k}\left(r_i, t\right)\right]} \tag{4}$$

where $T_{j,k}$ (r_i,t) presents the transient temperature at radius r_i within each j-th step $\Delta t_{j,k}$ of the daily load cycle. $E(r_i)$ is the electric field. $L[E(r_i),T(r_i,t)]$ is life at constant temperature.

By introducing the scale parameter of the applied electrothermal stresses, the reliability at mission time t_F of HVAC cables subjected to seasonal values of load cycles and varied soil parameters can be estimated [22]:

$$R\left(t_F\right) = \exp\left(-\left(\frac{t_F}{L_y}\right)^{\beta_t}\left(-\ln\left(1-P_D\right)\right)\right) \tag{5}$$

where L_y is the life in years; P_D is the design failure probability; β_t is the shape parameter.

Seasonal factors such as soil temperature, thermal resistivity of the soil and daily load cycles were considered in the electrothermal life model. The results indicated that soil resistivity and temperature played dominant roles in the fraction of life and reliability loss of submarine cable insulation [22]. The hot (summer) season presented a high loss of cable life and reliability [22]. Further research should focus on the cumulative ageing approach for the cable evaluation by the effects of voltage surges, thermomechanical stresses and dynamic load cycles.

6 | CONCLUSION

This study summarised and discussed the failure of submarine cables for high-voltage power transmission. The main conclusions are as follows:

1. External aggression, such as fishing and anchoring, accounted for a dominant percentage of cable failure statistics. The short fault was the most common failure caused by insulation breakdown. Cable fault analysis included the measurements and the function of optical fiber.
2. Insulation breakdown was the final fault result of almost all cable failures (except for optical fiber fault). Possible failure mechanisms were discussed, which were mainly ascribed to mechanical and electrothermal failures.
3. Space charge, electrical and water tree, PDs, and overvoltage with electromagnetic transient (EMT) caused cable degradation. Cable deformation by anchoring caused a threat to failure. Some defects were formed by mechanical pressure. Besides, the non-linear strain and stress of the cable materials could accelerate the electrothermal degradation.

Some key issues and prospects were considered and provided for the future development of HV submarine cables. Particularly, some new methods were recently proposed and studied for submarine cable development. For instance, protection methods of cable from anchoring, suppression and diagnosis methods for electrical and water tree degradation were proposed. New models and methods for calculating and estimating the cable parameters were studied. Future prospects related to the cable failure especially for insulation ageing by treeing and electrothermal effects were also discussed.

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