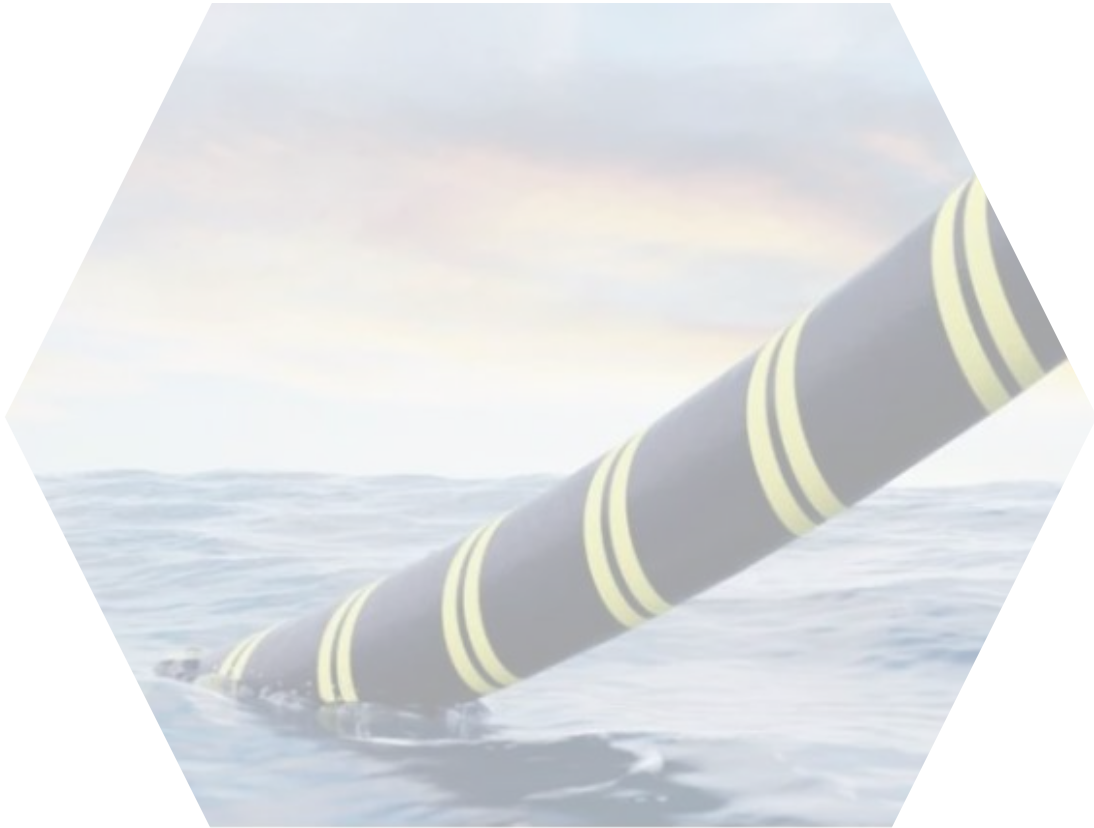




D5.1



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EXECUTIVE SUMMARY

The deliverable **D5.1 – HVDC cable ageing mechanisms study** covers research on ageing mechanisms that occur during the operation of HVDC cables and how their condition could be monitored and assessed using fibre-optic-based sensors.

Therefore, it includes two clearly differentiated areas:

1. **Description of ageing mechanisms** and their relationship with different types of fibre-optic sensors.
2. **Application of sensors**, their arrangement, and data usage to achieve the final goal of monitoring and predicting HVDC cable ageing.

These areas can be summarised into two main sections in the report:

- **Ageing mechanisms:** Describes ageing mechanisms, their performance in different scenarios, and the measurable variables related to ageing.
- **Optical fibre-based sensors:** Explains the operating principle of different sensors and the variables they measure for HVDC cable ageing monitoring.

Expected Outcomes

Deliverable D5.1 sets the stage for the description of different **ageing mechanisms** like:

- **space charge: Degradation of the insulation due to field improvement**
- **Partial discharge:** Degradation due to localised dielectric breakdowns in voids or defects
- **Electrical trees:** Degradation due to tree-like paths within the insulation due to high local electric fields, often initiated by PD activity.

Each of these mechanisms is associated with measurable physical variables — such as electric field, temperature, etc. — which can be targeted using appropriate sensing technologies as in section 2.



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ABBREVIATIONS AND ACRONYMS

Abbreviations / Acronyms	Description
HVDC	High Voltage Direct Current
PD	Partial discharge
XLPE	Cross-Linked Polyethylene
FC	Fibre Optic Sensor
ET	Electrical Trees
DE	Dielectric Breakdown
D	Electric Displacement
DAS	Distributed Acoustic Sensing sensors.
FBG	Fiber Bragg Grating sensors
DTS	Distributed Temperature Sensing



1 INTRODUCTION

This report is part of the **EasyDC-FOS**, which arises from the increasing interest in HVDC cable systems for power transmission. These systems are more efficient over long distances compared to HVAC cables, where energy losses become significant. However, several mechanisms can degrade the cable insulation, potentially reducing its efficiency and even leading to total failure if a proper monitoring and maintenance strategy is not in place to extend the cable's lifespan and enhance its robustness from both a functional and economic perspective.

The report covers topics related to HVDC cable ageing mechanisms and their monitoring using fibre-optic sensors.

To this end, the report is structured as follows:

Section 2 - Ageing mechanisms

Subsection 2.1 provides a description of ageing in HVDC cables, which is essential for identifying the mechanisms that impact the cable's lifespan while **Subsection 2.2** outlines the mechanisms that can be measured using fibre-optic sensors, covering inception phenomena, the influence of different operating conditions on ageing rates, and finally, the partial and final effects on the insulation.

Section 3 - Optical fibre-based sensors for ageing measurement

Subsection 3.1 introduces fibre-optic sensors capable of monitoring ageing, explaining their operating principle, which depends on the variables they measure that indicate ageing indirectly.

Additionally, it discusses the types of sensors, their application and integration, and how a combination of different sensors can enhance ageing monitoring robustness.

The final subsection describes error sources in fibre-optic sensors and possible mitigation strategies.

Section 4 - Benefits and challenges

The final section reviews the main benefits of fibre-optic sensors compared to conventional sensors used for ageing monitoring, as well as the challenges these sensors may face.

2 Ageing Mechanisms

2.1 Ageing in HVDC cables

There are various causes of premature failure in HVDC cables, which may be triggered by manufacturing defects, poor installation, and external factors. However, during the operational life of these cables, different types of stress can arise that need to be monitored, as they may be intensified by initial defects, potentially leading to electrical failure much earlier if a predictive maintenance strategy is not in place.

To define an electrical failure, we can consider the leakage current that typically appears in cable insulators. Ideally, even if the stress under which the cable operates increases, the leakage current should remain insignificant and stable, even if the behaviour ceases to be linear concerning the applied stress.

However, when a critical threshold of electrical stress is exceeded, the leakage current increases by several orders of magnitude (becoming unstable) without the need for further stress escalation.

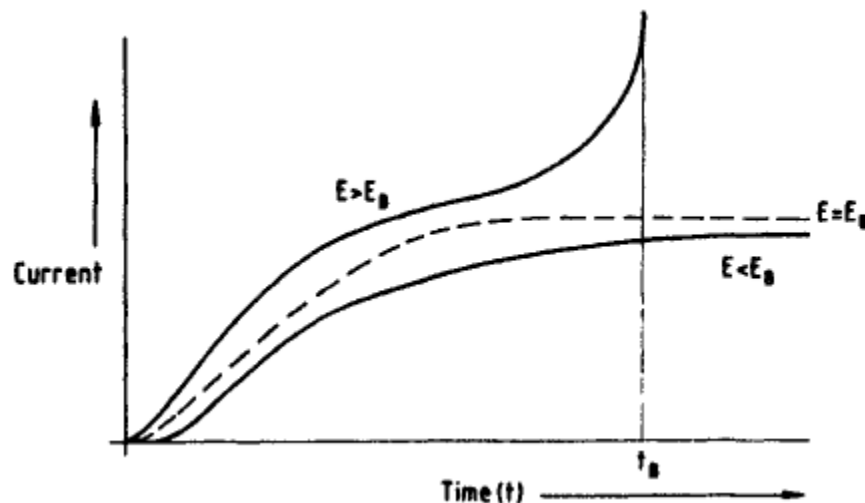


Figure 1 Breakdown for insulation vs Electric field [1]

For this behaviour to persist, there must be a mechanism that alters certain properties of the material (degrading it and modifying its dielectric properties), sustaining the increase in current, which we will discuss in the next section, and which leads to the ageing of the insulation.

Before a failure occurs, electrical ageing plays a crucial role, making it essential to understand the different ageing mechanisms to which these cables are exposed during operation:

- Electrical
- Thermal

- Environmental

Depending on the type of operation, which can be either standard or occur sporadically, these mechanisms may be intensified and accelerate electrical ageing.

In Figure 2, the main modes that can generate stress are identified, showing how these stresses can create a feedback effect, potentially leading from a temporary failure to a total failure.

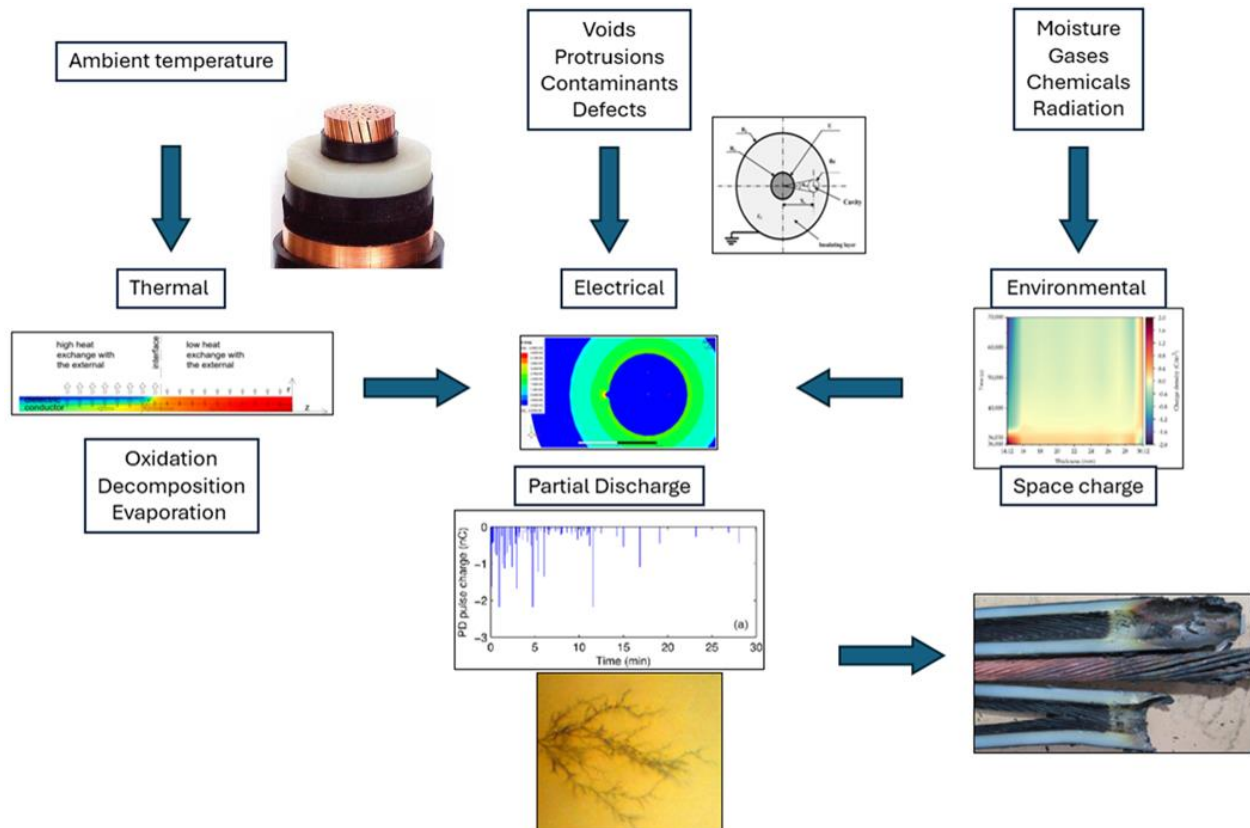


Figure 2 Ageing mechanisms

2.2 Ageing due to space charge distribution

The accumulation of space charge in HVDC cables is a critical phenomenon that affects the electric distribution within the insulation, potentially causing long-term detrimental effects on cable performance and lifespan. This accumulation as can be seen in Figure 3 can lead to modifications in the molecular structure of the insulating material and the possible initiation of partial discharges, which, in turn, induce local changes in dielectric properties. These changes may create conductive pathways (electrical trees), ultimately leading to total insulation failure.

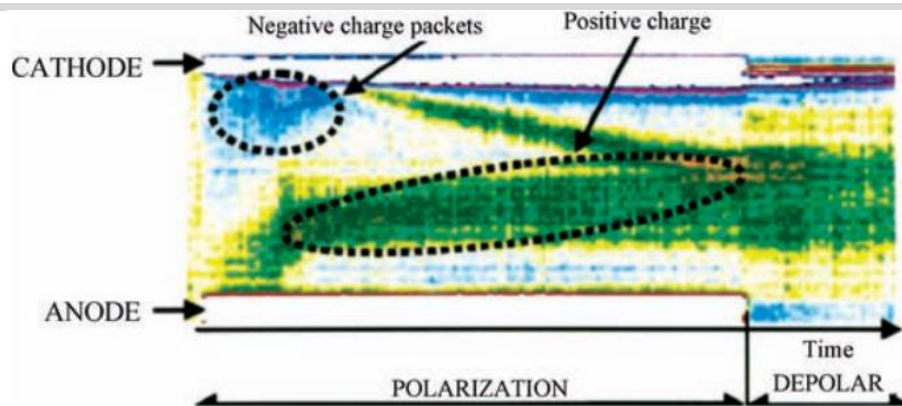


Figure 3 Space charge accumulation [16]

2.2.1 Inception Factors

Several factors influence the formation of space charge. The most relevant ones include:

- Charge Injection from Electrodes

Charge carriers can be injected from the electrodes into the insulation, depending on the conditions of the electrode-insulation interface due to the existence of a Coulombic potential barrier that must be overcome and the thermal energy of the charges.

This barrier can be reduced by high electric fields (as in our case), increasing the probability of charge injection into the insulation. This process is known as **Schottky injection** and can be visualized in the following image:

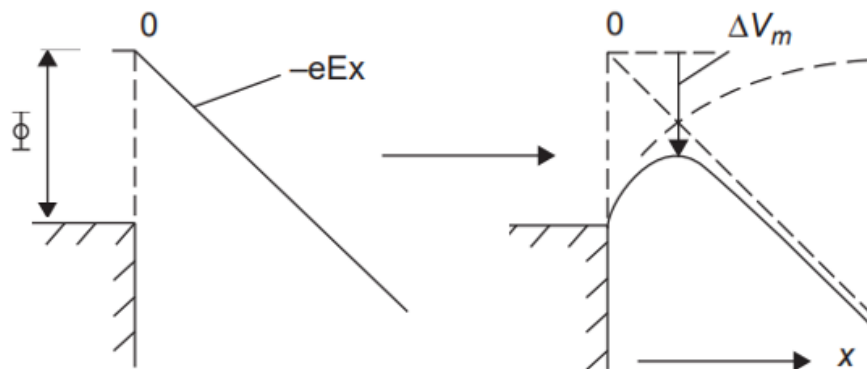


Figure 4 Schottky injection [2]

- Charge Transport and Trapping

Apart from charge injections, understanding the charge transport mechanism within the insulator is essential.

It is influenced by the atomic and molecular structure of the insulating material (polymers), where various manufacturing and operational processes lead to the formation of compounds such as additives used to stabilize the polymer (e.g., thermal oxidation inhibitors) or irregularities in the packing of polymer chains, micro-voids, amorphous regions in the material, etc.

These defects cause the energy bands (energy regions available for electrons), as shown in Figure 5, to become diffuse, as opposed to what happens at low electric fields.

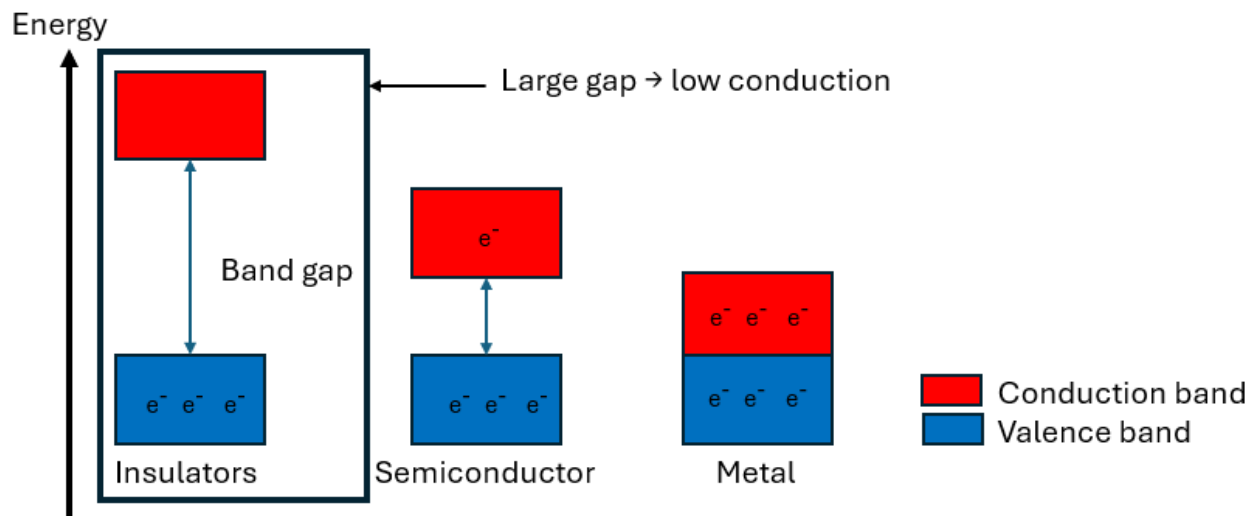


Figure 5 Ideal band diagram

The mentioned diffuse band can be observed in Figure 6, where the trap density in the insulation is shown, where traps are charge trapping regions, caused by the defects mentioned earlier. Depending on the region we are in, there can be surface traps (close to the mobility edge), where the traps are very close to each other, allowing the hopping process to occur more frequently, generating an electric current. On the other hand, in areas closer to the centre of the gap, the trapping of charges is more enduring, modifying the material's conductivity.

Deep traps are usually caused by the presence of chemical compounds (such as those mentioned earlier), while shallow traps result from irregularities in the material's structure, as described above.

For electric charges to escape from these traps, they must overcome the trap's energy depth, which is typically greater than 0.5 eV for deep traps and lower for shallow traps.

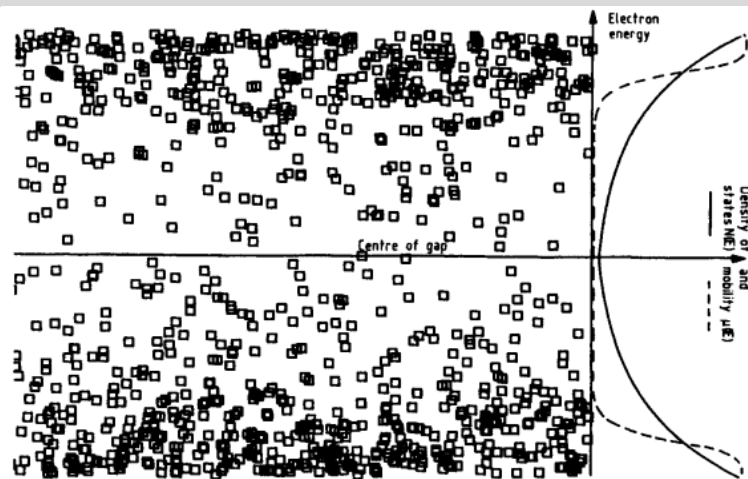


Figure 6 Density of traps [1]

As mentioned, the material's conductivity strongly depends on the density and depth of these traps. For example, if a significant density of deep traps is present at the conductor-insulator interface, that region can trap charges for long periods, which may reduce the electric field, thereby decreasing charge injection and ultimately limiting space charge density.

- Temperature Gradients and Conductivity

The spatial variation of insulation conductivity, combined with thermal gradients, can induce localized charge accumulation. This occurs because temperature gradients cause charge injections at the conductor-insulator interface and simultaneously modify the conductivity, resulting in differences in the mobility of the charge carriers.

For example, the temperature in the system could cause the injection process to dominate over charge transport in the insulator.

If we consider moderately low temperatures, the charge injection could be very small, and so would its transport, favouring the accumulation of space charge. On the other hand, at high temperatures, although charge injections are high, transport is also enhanced, meaning that space charge accumulation could be more evenly distributed within the material. As shown in Figure 7, at higher temperatures, the charge gradually spreads toward the interior of the material.

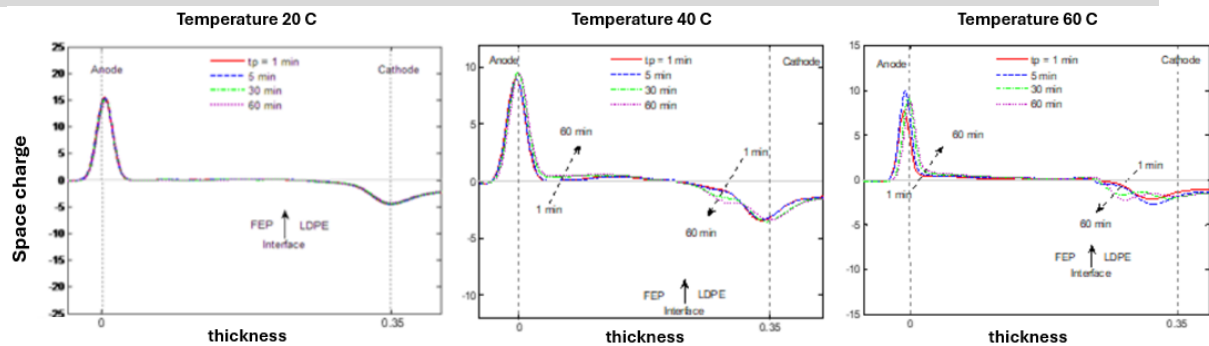


Figure 7 space charge vs temperature [18]

This localized accumulation of charge can distort the electric field, leading to further degradation of the insulation material and an increased likelihood of partial discharges, which can accelerate insulation failure over time.

- Pre-existing charge in polymer

Due to manufacturing processes or previous exposure to electrical fields, pre-existing charges within the polymer can contribute to space charge formation, especially in areas where the material experiences higher electric fields affecting the charge transport and distribution within the material. These effects can alter the polymer's dielectric properties, including its conductivity and susceptibility to partial discharges.

For example, additives are often added to insulators to inhibit thermal oxidation, or in the case of manufacturing, residual peroxides are typically formed (during the crosslinking of XLPE polyethylene).

When exposed to significant electric fields, these compounds can dissociate into mobile ions, which can be transported, altering the electric field and potentially acting as traps for other charges.

2.2.2 Influence of operating conditions

- Current Load and Temperature

The current in the cable modifies the temperature distribution in the insulation which can have an impact on the conductivity of the material leading to space charge accumulation.

Due to the Joule Heating effect, at a higher current more are the resistive losses, and the cable temperature increases too.

Higher temperatures contribute to charge mobility (in the zone of shallow traps) as they can have more energy to hop from one trap to another one and as consequence, conductivity is enhanced.

The charge accumulation distribution can be modified due to different transients and as consequence, field enhancement can occur with the inception of partial discharges.

- Voltage Polarity

Polarity reversals can alter the charge distribution, affecting the reliability of the insulation.

This occurs because the type of charge injected at the electrode's changes, and when combined with the pre-existing charge distribution, the electric field can become intensified. This field enhancement can lead to structural modifications in the material, such as changes in the trap distribution, ultimately altering the material's resistance properties.

If these effects are not properly managed, repeated polarity reversals can accelerate insulation degradation, increasing the risk of partial discharges and electrical breakdown over time.

- Operating time

Over time, cable operation can lead to increased charge accumulation and, consequently, material degradation.

This type of accumulation often occurs because many traps gradually fill with charge, converting shallow traps into deep traps. As a result, the material's conductivity decreases, and its dielectric properties change.

These changes in dielectric properties contribute to aging mechanisms such as partial discharges and electrical treeing, which can ultimately lead to insulation failure if not properly managed.

2.2.3 Partial and final effects

- Immediate Effects

- Electric field distortion within the insulation, increasing the risk of failure.
- Formation of heterocharge and homocharge:

Homocharges are trapped charges in the dielectric that have the same sign as the surface charge of the adjacent electrodes, making charge injection more favourable. In contrast, heterocharges have the opposite sign, meaning that charge transport plays a more significant role than injection as can be seen in the Figure 8, where we can observe an intensification of the electric field inside the material due to homocharges and in the electrode region due to heterocharges.

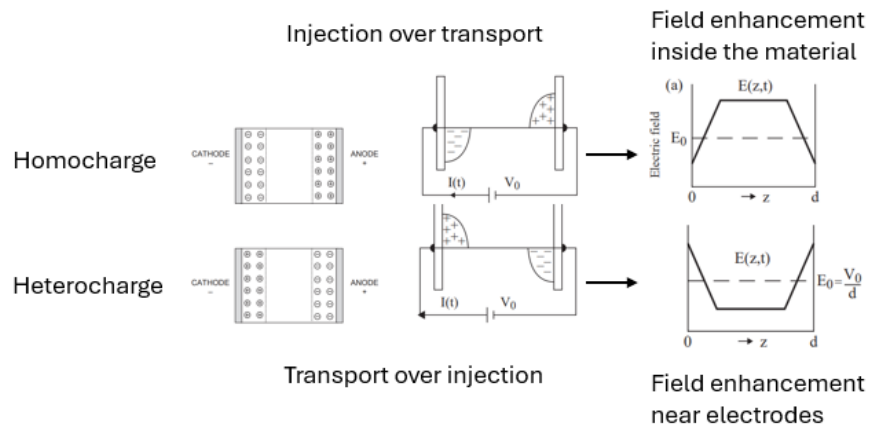


Figure 8 Types of space charge distribution [2]

- Possible field inversion due to charge redistribution influenced by temperature and conductivity gradients.
- Long-Term Effects
 - Accelerated insulation aging: Space charge can induce additional stress in certain regions of the cable, accelerating material degradation.
 - Risk of partial discharges: Localized charge accumulation can create regions with high field gradients, promoting the initiation of partial discharges.
 - Premature failures: In extreme cases, space charge can lead to dielectric breakdown of the insulation, reducing the cable's lifespan.

2.3 Partial discharge

Partial discharges are electrical discharges that occur in certain areas of the cable insulation without causing a complete dielectric breakdown. These discharges are a critical phenomenon in the aging and degradation of insulating materials because, with frequent occurrences, they can lead to final breakdown (electrical path inside the insulation).

2.3.1 Inception Factors

Partial discharges in HVDC cables can be caused by various factors, including:

- Imperfections in the insulation
 - Voids, impurities, and contaminants

During the cable manufacturing process, small air-gas bubbles can form within the insulation. The permittivity (ϵ_r) of these bubbles is lower than that of the insulation,

causing an increase in the electric field because the electric displacement (D) must remain continuous:

$$D = (\epsilon_r \cdot E)_{void} = (\epsilon_r \cdot E)_{insulation}$$

$$E_{void} > E_{insulation}$$

Additionally, since cavities can have surfaces with sharp edges or small curvature radii, the charge density (σ) may increase due to several factors, leading to intensified electric fields.

That could ionize the gas if it exceeds the dielectric breakdown threshold of the gas.

- Charge space accumulation
 - The space charge trapped in the insulation can distort the electric field distribution, creating regions with a higher field than expected, which can promote the initiation of partial discharges.
- Environmental and operating conditions
 - Temperature and thermal gradient

Temperature can improve the conditions for the occurrence of partial discharges because, as mentioned, dielectric breakdown can be reduced at higher temperatures.

Additionally, due to this, the space charge could increase significantly in certain areas.

Possible expansions/compressions (mechanical stresses) of the material can also occur due to thermal gradients, which may lead to fractures and cracks—areas that facilitate the formation of partial discharges.
 - Humidity

Humidity is another factor that can worsen the dielectric strength of the material. With temperature changes, humidity can condense in certain areas and could improve the conditions for the occurrence of partial discharges.

2.3.2 Influence of operating conditions

The operating conditions in HVDC systems affect the initiation and evolution of partial discharges:

- Voltage intensity and polarity

In AC, PDs can occur in each cycle, while in DC, the frequency of PDs is much lower. However, if there is a polarity inversion in HVDC, this can cause a redistribution of charge



that leads to new partial discharges if the voltage overcomes the voltage inception where the dielectric resistance is overwhelmed.

- Thermal gradients

Temperature gradients can induce mechanical stress in the insulation, which can create new microcavities or amplify existing defects, favouring the occurrence of PDs.

- Operating time and material aging

Over time, partial discharges can slowly erode the cable's insulation. As the insulation ages, the likelihood of failures due to partial discharges increases.

This erosion is due to the avalanche effect of electrons and ionization of the gases inside the void.

2.3.3 Partial and final effects

Partial discharges have a progressive impact on the insulation of HVDC cables, which can be divided into two stages:

- Partial effects (initial)
 - Alteration of the electric field: Partial discharges can modify the electric field distribution within the insulation, favouring the occurrence of more PDs as can be seen in the figure 9:

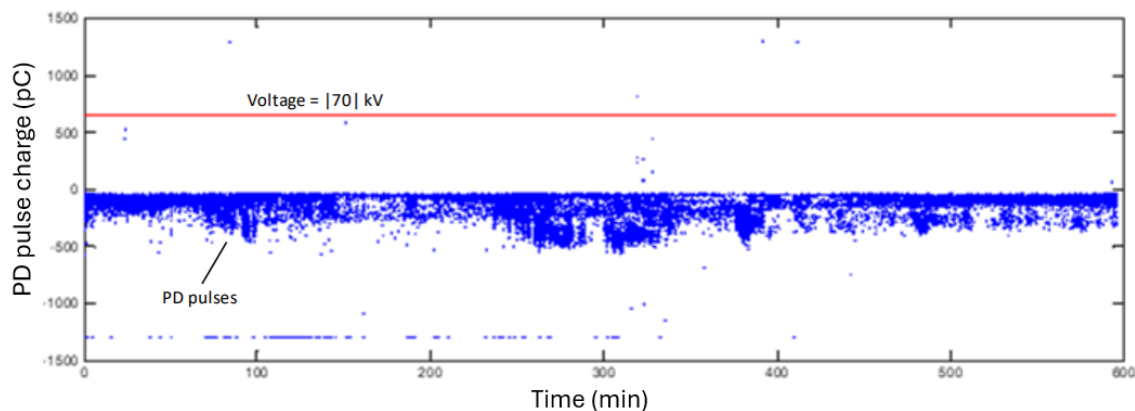


Figure 9 Occurrence of PD vs time [17]

- Formation of localized damage: Repeated discharges at the same point can create areas of weakness in the material.
- Final effects (insulation failure)

- Chemical and thermal degradation: PDs can generate localized heat and chemical by-products that alter the composition of the insulation.
- Growth of electrical trees: PDs can expand small cracks within the insulation, forming conductive paths that eventually lead to dielectric breakdown of the cable.
- Catastrophic failure of the cable: If partial discharges continue without detection or mitigation, the insulation can fail completely, causing a fault in the HVDC line.

2.4 Thermal effects and gradient temperature

Thermal effects and temperature gradients in HVDC cables are critical factors that affect the accumulation of space charge, the distribution of the electric field, and the reliability of the insulation.

2.4.1 Inception Factors

Thermal effects in HVDC cables result from energy dissipation in the form of heat, which creates a temperature gradient within the insulation. The main causes are:

- **Joule losses:** The resistance of the conductor generates heat as current flows, increasing the temperature in the core of the cable.
- **Cooling conditions:** The dissipation of heat depends on the cable installation (buried, submerged, or exposed) and the surrounding medium.
- **Variations in system load:** Changes in the load current affect heat generation and the thermal stability of the insulation.
- **Differences in thermal conductivity of materials:** Insulating materials have different capacities to dissipate heat, which affects the thermal homogeneity of the cable.

2.4.2 Influence of operating conditions

Operating conditions play a key role in the formation of thermal gradients, which can affect the distribution of the electric field and the accumulation of space charge.

- **Radial thermal gradient**
 - The temperature in the insulation decreases from the hot conductor to the colder outer shield.
 - This temperature gradient causes an electrical conductivity gradient, altering the electric field distribution within the insulation.
- **Changes in ambient temperature**



- In buried cables, soil temperature influences thermal dissipation. In cold climates, permafrost can form, reducing the cable's cooling capacity.
- In cables exposed to the open air or in tunnels, temperature variations can induce heating and cooling cycles that affect the aging of the insulation.
- **Influence on space charge accumulation**
 - A significant thermal gradient alters the mobility of charge carriers, favouring the redistribution of space charge within the insulation.
 - In some cases, an increase in temperature reduces charge accumulation, while in others, it can promote the formation of heterocharge in specific regions of the cable.

2.4.3 Partial and final effects

Thermal effects can accelerate the aging of insulation and affect the reliability of the HVDC cable.

- **Partial effects (initial)**
 - **Redistribution of the electric field:** The thermal gradient causes variations in conductivity, altering the electric field distribution and increasing stress in certain regions of the insulation.
 - **Increased mobility of trapped charges:** The rise in temperature can release trapped charges in insulation defects, promoting partial discharges.
- **Final effects (insulation failure)**
 - **Thermal degradation:** High temperatures can cause chemical degradation of the insulating material, reducing its dielectric strength.
 - **Failure due to electric field inversion:** In some cases, the thermal gradient can lead to space charge accumulation that inverts the electric field in certain regions of the insulation, increasing the risk of dielectric failure.
 - **Insulation collapse:** A combination of thermal gradients, space charge, and mechanical aging can lead to catastrophic cable failure.

2.5 Electrical Tree (ET)

ETs are pre-breakdown mechanisms with a branched structure resembling tree, as shown in Figure 10.

The development of this structure can irreversibly degrade the polymeric insulation of HVDC cables, leading to total failure when it completely penetrates the insulation or encounters the cable's electrodes.



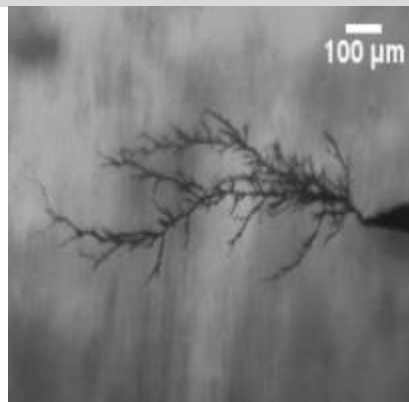


Figure 10 Electrical tree [10]

2.5.1 Inception Factors

- **Partial discharges:**

Partial discharges expand the cavity structure, removing material either through the impact of electrons on the cavity walls or through chemical reactions that also degrade the insulation.

Although the electric field decreases after a partial discharge due to charge distribution, it can exceed the dielectric strength of the gas inside the cavity again, as the voltage conditions are steady.

Furthermore, the expansion of the void or defect can lead to a further intensification of the electric field, improving the conditions for the occurrence of electrical discharges.

In general, PDs are a mechanism that generates ETs, but at the same time, with the appearance of the latter, the conditions for PDs improve, making these two mechanisms mutually reinforcing.

- **Space charge**

Because space charge can increase the electric field, it weakens the covalent bonds of the insulator, which can accelerate the degradation of the insulation, increasing the branching and the conditions for PDs.

- **Thermal effects**

The increase in temperature improves charge conduction, so in specific areas, charges could concentrate, accelerating electrical degradation.

Similarly, dielectric strength tends to decrease as temperature increases, making partial discharges more frequent. Additionally, thermal oxidation in voids accelerates, promoting the expansion of the branches.

If we also consider the presence of thermal gradients, differences in charge mobility occur, creating areas of charge accumulation, along with internal mechanical stresses that could generate microcracks, which are ideal regions for the formation of ETs.

2.5.2 Influence of operating conditions

Operating conditions play a key role in the formation of electrical trees, which can affect the degradation of the insulation.

- Transient development until a steady accumulation
 - Since the charging voltage is applied, the electric field begins to evolve, and charge accumulates at different points within the insulator.
 - During the transient period, weak spots may appear due to the transient electric field, as well as mobile traps where partial discharges could occur.
- **Changes in charge**
 - Changes in charge can lead to temperature fluctuations as well as changes in the electric field, creating mechanical and thermal stress that could produce traps, favouring charge accumulation.
- **Influence of polarity changes or charge shutdown**
 - Considering a polarity change, as seen in Figure 11.

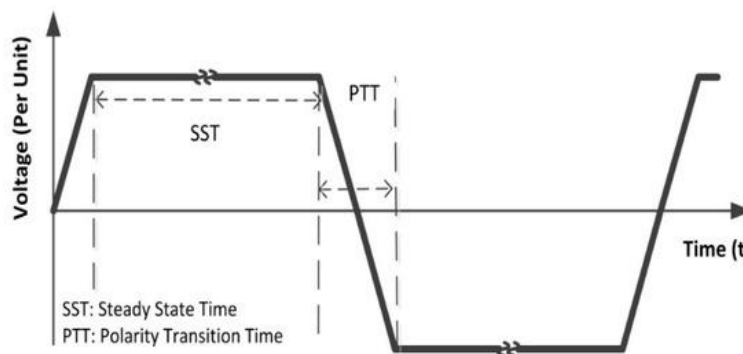


Figure 11 Inverse of polarity [10]

If the change is almost instantaneous, the space charge accumulated in the insulator must be distributed quickly, which could lead to partial discharges.

There could also be areas that weaken further due to the additional stress caused by the accumulated charge that needs to be redistributed.

2.5.3 Partial and final effects

Electrical trees can accelerate the aging of insulation and affect the reliability of the HVDC cable.

- **Partial effects (initial)**
 - **Partial discharges:** Although initially PDs are the cause of ETs, the appearance of the latter accelerates the occurrence of partial discharges and the degradation of the insulator.
 - **Changes in the insulator structure:** The more frequent occurrence of PDs leads to more microcracks, which alter the dielectric properties of the insulator.
 - **Thermal degradation:** The frequent release of energy increases the local temperature, causing degradation through thermal processes such as thermal oxidation.
 - **Distortion of the electric field:** The branches are points of intensification of the electric field.
- **Final effects (insulation failure)**
 - **Total failure:** If they develop to the point of connecting with the cable electrode, they can directly cause the dielectric breakdown (DE) of the insulator, leading to failures in the cable or the insulation system.
 - **Loss of reliability:** DE leads to frequent operational shutdowns, which could cause failures in other equipment, as well as maintenance costs or electrical supply failures.

2.6 Environmental

HVDC cables are exposed to various environmental conditions that can affect their performance, longevity, and reliability. Factors such as humidity, pollution, extreme temperatures, and the mechanical conditions of the terrain can accelerate the aging of the insulation and increase the risk of failures.

2.6.1 Inception Factors

The main environmental factors that influence HVDC cables include:

- **Humidity and water penetration - Water trees**
 - Humidity can affect the insulation through the diffusion of water into the polymeric material.

In humid environments, such as in the case of submarine cables, dendritic growth of micro-defects can occur inside the cable's insulation. These dendrites consist of



helical water pockets connected by tubular channels, which are also filled with water.

- In cables with inadequate protection, water can infiltrate and form water trees, deteriorating the dielectric strength of the insulation.

Since many polymers are large water absorbers, water can infiltrate cavities or microcracks within the insulator. Once inside, in the presence of the electric field, various processes can occur, such as water polarization, which would weaken the covalent bonds of the polymer chains, chemical reactions with the insulator due to free radicals or ions that may be present in the water.

All these processes cause the expansion of microcavities and considering that the water infiltrates deeper into the material, ion transport within it becomes inevitable due to the electric field. This means of transport leads to new chemical reactions that continue to branch out the material, as shown in Figure 12:

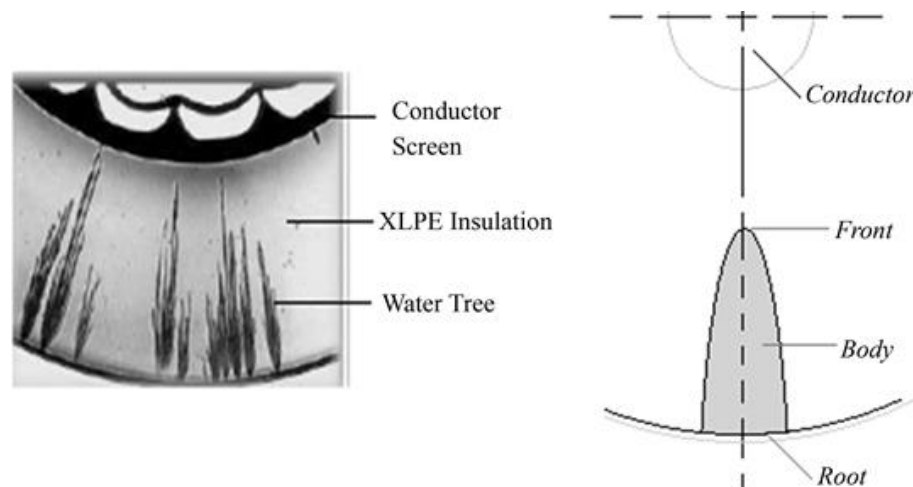


Figure 12 Water trees [19]

The shape of these trees mainly depends on the applied voltage, the frequency (since it promotes greater ionic mobility due to the oscillating field), and the absorption characteristics of the insulator.

The problem with this type of mechanism is that it causes a change in the material's structure, reducing its dielectric strength and thereby facilitating the occurrence of partial discharges.

- **Pollution and corrosion**

- Exposure to industrial or marine environments can cause the accumulation of salts and pollutants on the cable's outer cover.

- In submarine cables, contact with seawater can cause galvanic corrosion in the metallic protective layers.
- **Extreme temperatures and permafrost**
 - In cold climates, permafrost can increase the rigidity of the soil and affect the thermal dissipation of the cable.
 - In warm regions, high temperatures can raise the insulation temperature, affecting its conductivity and accelerating thermal aging.
 - Rapid temperature changes can cause mechanical stress in the insulation due to thermal expansion and contraction. Considering cycles that could affect certain areas, microcracks may open, increasing the permeability to moisture.
- **Mechanical stress and vibrations**
 - During the installation and subsequent operation of the cables, mechanical stresses can arise.
 - For example, cables buried in unstable terrain may be subjected to soil movement, creating additional mechanical stresses.
 - In underwater installations, marine currents and wave action can induce repetitive stress on the cable structure.
 - All these originating stresses can result in the formation of microcracks, weakening the structure and electrical properties of the material.

2.6.2 Influence of operating conditions

Operating conditions interact with the environment and can exacerbate the environmental effects on HVDC cables:

- **Electrical load and temperature:**

According to the operating conditions, we could encounter, as in the case of electrical trees, the growth of water trees due to transient events, such as a polarity change, or impulses superimposed on the constant operating voltage. These events, in addition to the long periods' characteristic of normal operation, cause transients in the electric field that can ionize compounds and transport them, thus facilitating electrochemical degradation and the growth of water trees.

- **Electric field distribution:**

Humidity and pollution can alter the electric field distribution, promoting the formation of partial discharges.



2.6.3 Partial and final effects

Environmental effects can be progressive, starting with mild degradation and culminating in catastrophic failures:

- **Partial effects (initial)**
 - Increased insulation conductivity due to moisture absorption and the growth of electrical trees and water trees.
 - Formation of microcracks due to thermal expansion and contraction.
 - Localized corrosion in the metallic screen and outer cover.
- **Final effects (insulation failure)**
 - Dielectric collapse due to insulation degradation.
 - Mechanical failure of the cable due to structural fatigue induced by mechanical and thermal stress.
 - Loss of sealing and electrical failure due to water infiltration and corrosion.



3 OPTICAL FIBRE-BASED SENSORS

Optical fibre sensors have emerged as an advanced technology for monitoring high-voltage electrical systems, including HVDC (High Voltage Direct Current) cables. Due to their ability to operate in extreme environments, provide high precision, and allow distributed measurements over large distances, they have become a key tool for diagnostics and predictive maintenance in critical electrical infrastructure.

An optical fibre sensor relies on the transmission and manipulation of light within an optical fibre to detect changes in its environment. Depending on the operating principle, these sensors can measure temperature, mechanical stress, space charge, partial discharges, and environmental conditions, providing real-time data without the need for direct contact with the conductor or insulation.

The main benefits of optical fibre sensors include:

- Immunity to electromagnetic interference, making them ideal for high-voltage systems applications.
- Distributed monitoring capability, allowing spatially resolved measurement of variables along the entire length of the cable rather than at isolated points.
- High sensitivity and precision, with resolutions in the nanometre range for deformations and millikelvins for temperature.
- Durability and resistance, as they can operate in harsh environments without significant degradation.

These sensors can be classified into two main types:

- Distributed sensors, which provide continuous spatially resolved information along the cable, such as Distributed Temperature Sensing (DTS) sensors or Distributed Acoustic Sensing (DAS) sensors.
- Point-based sensors, such as Fibre Bragg Grating (FBG) sensors, which are installed in critical locations for localized monitoring.

In HVDC cables, the implementation of optical fibre sensors is crucial for preventing failures and optimizing maintenance. Their integration with advanced analysis systems and predictive models allows for detecting anomalies before catastrophic failures occur, reducing operational costs and improving system reliability.

The following outlines the different types of sensors based on each aging mechanism presented in the previous sections:



3.1 Optical Fibre Sensors for Space Charge Detection in HVDC Cables

Space charge in HVDC cables affects the distribution of the electric field and can lead to dielectric failures. To detect it, optical fibre sensors based on electro-optic and interferometric effects are used, which allow for measuring the electric field and charge accumulation.

3.1.1 Electro-Optic Sensors Based on the Pockels and Kerr Effect

3.1.1.1 Monitored Aging Mechanism

- Space charge: It measures the distortion of the electric field caused by the accumulation of charge in the cable insulation.

3.1.1.2 Operating principle

- Pockels Effect:

The refractive index of the electro-optic material changes linearly with the electric field, altering the polarization of the light in the optical fibre.

- Kerr Effect:

Like the Pockels effect, but the change in the refractive index is proportional to the square of the electric field.

3.1.1.3 Types of sensors

- Point-based (localized):

They are installed at strategic points to measure the electric field in areas of higher space charge accumulation.

- Distributed (less common):

Implemented at multiple points along the cable to obtain a map of the space charge.

3.1.1.4 Application and integration in ageing monitoring

- Measurement of the internal electric field of the cable to detect anomalous accumulations of space charge.
- Analysis of space charge redistribution based on operating conditions (temperature, voltage, polarity changes).

- Prediction of partial discharges by detecting charge accumulation at critical points of the insulation.
- Comparison with partial discharge sensors (DAS, PEA) to analyse the relationship between space charge and dielectric failures.
- Use in simulation models in COMSOL and ANSYS to predict the evolution of space charge and its impact on cable performance.
- Correlation with temperature sensors (DTS, FBG) to evaluate the influence of thermal gradients on space charge mobility.

3.1.1.5 Sources of errors and their mitigation in aging monitoring.

- Error and mitigation 1:
 - Low sensitivity to weak electric fields, making early detection of space charge difficult.
 - Use of materials with higher electro-optic sensitivity or signal amplification.
- Error and mitigation 2:
 - Optical interference caused by mechanical vibrations or thermal fluctuations.
 - Implementation of thermal compensation systems and vibration-resistant mounting.
- Error and mitigation 3:
 - Noise in measurements due to electromagnetic disturbances from other high-voltage equipment.
 - Use of optical filters and noise-rejecting acquisition electronics.
- Error and mitigation 4:
 - Inadequate placement of the sensor, reducing its effectiveness in detecting space charge in critical areas.
 - Preliminary study of the electric field distribution in the cable to define the optimal placement.

3.1.2 Fibre Optic Interferometry-Based Sensors

3.1.2.1 Monitored Aging Mechanism

- Space charge: Detection of distortions in the electric field through optical phase measurements in the fibre.

3.1.2.2 Operating principle

- Mach-Zehnder Interferometry (MZI): It is based on the interference of two light beams that travel through different optical paths, where one of them is influenced by the electric field.
- Fabry-Pérot Interferometry (FPI): It uses a resonant cavity that changes its optical response depending on variations in the surrounding electric field.

3.1.2.3 Types of sensors

- Point-based (localized): Used at specific points along the cable to measure the electric field and detect accumulations of space charge.

3.1.2.4 Application and integration in ageing monitoring

- Measurement of the electric field induced by space charge in different regions of the insulation.
- Detection of electric field inversion, which may indicate charge accumulations that could lead to failures.
- Monitoring of the evolution of space charge over time to predict its impact on the cable's aging.
- Comparison with electroacoustic sensors (PEA) to analyse the distribution of space charge over time.
- Incorporation into SCADA platforms for remote monitoring and detection of anomalies in the cable's electric field.
- Combined use with temperature sensors (DTS, FBG) to analyse how the thermal gradient affects space charge accumulation.

3.1.2.5 Sources of errors and their mitigation in aging monitoring.

- Error and mitigation 1:
 - Sensitivity to mechanical vibrations, which can generate noise in the electric field measurement.
 - Mechanical isolation of the sensor or application of vibration filtering algorithms.



- Error and mitigation 2:
 - Difficulty distinguishing between electric field fluctuations and actual space charge effects.
 - Use of redundant sensors at different points for data comparison.
- Error and mitigation 3:
 - Low response in uniform electric field conditions, which may cause certain space charge phenomena to go unnoticed.
 - Implementation of periodic measurements with trend detection algorithms.

3.2 Optical Fibre Sensors for the Detection of Thermal Effects in HVDC Cables

3.2.1 Fibre Bragg Grating (FBG) Sensors

3.2.1.1 Monitored Aging Mechanism

- Gradients and thermal effects (temperature variations in the cable).
- Mechanical stresses and deformations (tensions in the insulation due to ground movements or thermal expansion).

3.2.1.2 Operating principle

FBG sensors are based on a Bragg grating inscribed in the optical fibre, which reflects a specific wavelength of light. When the sensor experiences changes in temperature or mechanical stress, the reflected wavelength varies proportionally, allowing these changes to be detected with high precision.

3.2.1.3 Types of sensors

- Point-based (located at specific points): They are installed at splices, terminations, and critical areas of the cable.
- Multiplexed: Multiple FBG sensors can be placed on a single fibre to obtain data from multiple points.

3.2.1.4 Application and integration in ageing monitoring

- Measurement of temperature distribution to identify overheating points in the HVDC cable.
- Monitoring of mechanical stresses in the insulation to detect deformations due to changes in thermal load or ground displacement.

- FBG data can be combined with DTS sensors to validate temperature distribution over long distances.

3.2.1.5 Sources of errors and their mitigation in ageing monitoring.

- Wavelength deviation caused by contamination in the optical fibre.
- Poor calibration leading to errors in correlating thermal variations with mechanical displacements.
- Placement in areas with low thermal dissipation, reducing the ability to detect critical overheating.

3.2.2 DTS - Distributed Temperature Sensing

3.2.2.1 Monitored Ageing Mechanism

- Thermal gradients and overheating in the HVDC cable.

3.2.2.2 Operating principle

DTS sensors are based on Raman or Brillouin backscatter, where the scattered light along the optical fibre is analysed to determine temperature variations at each point of the cable.

3.2.2.3 Types of sensors

- Distributed along the cable: A single sensor covers the entire length of the cable, allowing continuous monitoring.

3.2.2.4 Application and integration in ageing monitoring

- Detection of overheating areas that may accelerate the ageing of the insulation.
- Evaluation of heat dissipation efficiency in buried or submerged cables.
- Combination with FBG mechanical strain sensors to correlate temperature and deformations.
- Implementation in SCADA systems for real-time monitoring of the cable's thermal state.

3.2.2.5 Sources of errors and their mitigation in ageing monitoring.

- Low spatial resolution of Raman-DTS in long cables, which can hinder the accurate detection of hot spots.
- False readings due to optical interference in high pressure environments and hydrogen absorption occurs in the optical fiber, which is highly unlikely.

- Incorrect thermal compensation, such as time-interpolation between data to estimate true temperature points, predictive algorithms like Kalman filters, etcetc.,, affecting the accuracy of measurements in environments with rapid temperature fluctuations. This could happen if measurements are done slower than temperature changes.

3.3 Fibre Optic Sensors for Partial Discharge Detection in HVDC Cables

3.3.1 DAS - Distributed Acoustic Sensing

3.3.1.1 Monitored Ageing Mechanism

- Partial discharges (PDs) in the insulation.

3.3.1.2 Operating principle

DAS sensors use Rayleigh backscattering to detect acoustic vibrations along the cable. When a partial discharge occurs, it generates an acoustic wave that can be detected and accurately located.

3.3.1.3 Types of sensors

- Distributed: Continuous monitoring of partial discharges along the entire cable without the need for multiple point sensors.

3.3.1.4 Application and integration in ageing monitoring

- Early detection of PDs to prevent electrical failures in the insulation.
- Monitoring of partial discharges in joints and terminations, where they are more frequent.
- Comparison with electroacoustic PEA sensors to validate the presence of partial discharges.
- Use of artificial intelligence to analyse acoustic patterns and predict future failures.

3.3.1.5 Sources of errors and their mitigation in ageing monitoring.

- Difficulty distinguishing between PDs and environmental noise, which can generate false alarms.
- Lower sensitivity in cables with high mechanical shielding, as it can absorb part of the vibrations.
- Fibre misalignment issues, reducing the quality of the detected acoustic signal.

3.4 Fibre Optic Sensors for Humidity Detection in HVDC Cables

3.4.1 Humidity Sensors

3.4.1.1 Monitored Aging Mechanism

- Moisture penetration and insulation degradation.
- Mechanical stress on the cable is due to ground movements.

3.4.1.2 Operating principle

- Optical moisture sensors detect changes in infrared light absorption due to the presence of water.
- FBG pressure and strain sensors measure mechanical stresses in the cable sheath.

3.4.1.3 Types of sensors

- Distributed: Continuous monitoring in environments with a risk of water infiltration.
- Point-based: Installation at critical points such as joints or areas with high mechanical stress.

3.4.1.4 Application and integration in ageing monitoring

- Detection of moisture infiltration that may reduce the dielectric strength of the insulation.
- Evaluation of mechanical pressure changes in buried cables in unstable soils.
- Correlation with temperature sensors (DTS, FBG) to assess the combined impact of moisture and thermal gradients on insulation ageing.
- Integration into early warning systems for structural failures in buried or submarine cables.

3.4.1.5 Sources of errors and their mitigation in ageing monitoring.

- False detection of moisture due to surface condensation instead of actual infiltration.
- Pressure variations caused by transient conditions may generate erroneous readings of mechanical deformation.
- Reduced sensitivity in environments with high vibrations, which can affect the stability of the measurement.

4 CONCLUSIONS

This report has focused on the study of the main ageing mechanisms in HVDC cables.

Several factors have been identified that can degrade the polymeric insulators used in HVDC cables, thereby reducing their lifespan and performance under operational conditions. Among the primary ageing mechanisms, we found:

- Space Charge

This phenomenon is critical for understanding the evolution of degradation in HVDC cables over time. The accumulation of space charge can promote the degradation of the insulator due to the intensification of the electric field, favouring the occurrence of mechanisms such as partial discharges, ionization, charge transport, electrical trees, etc.

- Partial Discharge (PD)

The occurrence of partial discharges due to dielectric breakdown of gases inside voids, micro-cracks, etc. is essential to understand, as it gradually degrades the cavities and causes other irreversible mechanisms such as electrical trees.

- Electrical Trees

These are branches formed by the growth of cavities, micro-cracks, etc., and can lead to complete failure of the insulating system due to the frequent occurrence of partial discharges. Therefore, their monitoring is of vital importance.

- Environmental Mechanisms

Temperature, humidity, the presence of contaminants, etc., are environmental factors that can contribute to the ageing of the HVDC cable insulator. It is essential to consider these conditions when evaluating the durability and behaviour of the cables over the long term.

Therefore, it is of vital importance to measure and analyse monitored data from variables that are directly or indirectly related to these ageing mechanisms.

For this reason, this report also describes the main fibre optic sensors used in this industry, as they have proven to be an effective tool for monitoring these mechanisms continuously and non-invasively. Fibre sensors can detect changes in the properties of the insulating material, such as deformation, temperature, and charge concentration, enabling early and accurate monitoring of the ageing effects.



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