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State of the Art Review of High Voltage Insulation Monitoring

Master Thesis - Trond Berggreen

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By
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It is assumed that the reader has a moderate knowledge of electrical power engineering.

22.11.2021

Trond Berggreen

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Abstract

The devastating effects of global warming and climate change are now well understood and there is broad unity that fundamental changes are needed. This is clearly addressed in the United Nations Sustainable Development Goals of 2015. The main perpetrator contributing to global warming and climate change is how we consume energy, which will need to transition from fossil fuels to renewable energy. The mass integration of renewable energy sources aimed to mitigate the effects of global warming, will greatly alter how we generate, transmit and consume energy. If we combine this with the large shift in load consumption, due to the integration of electrical vehicles, there is no doubt that the electrical transmission system will be subjected to major changes in future decades. The existing transmission grid is an aged and mature system, with large parts being installed all the way back in 60s and 70s, thus nearing the end of service. The existing grid has continuous performance issues and the knowledge on fault and ageing mechanisms are still insufficient. A thorough assessment of the current state of the grid is necessary in order to properly gauge its ability to cope with mass integration of HV systems, predominantly HVDC. A key part in assessing the current state of the grid while simultaneously increase its resilience is the utilization of high voltage monitoring methods, as they are key to prevent and predict transmission faults. Due to the increased requirement of long distance high capacity transmission, especially in submarine conditions, the knowledge and monitoring of cables will be of high importance. Compared to AC technology, DC have been regarded as niche and specialist field, thus have been allocated far less attention and research, hence the knowledge and technology of DC is still limited. This thesis will assess the state of the art of high voltage monitoring while simultaneously explore its role towards achieving the UN Sustainable Development Goals.

Keywords: UN Sustainability Goals, Partial Discharges, Tan Delta, SF6, XLPE, High Voltage Monitoring, VLF

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Bergen, November 2021
Trond Berggreen.

Problem Description

What is the State of the Art of high voltage monitoring and how does it harmonize with the UN Sustainable Development Goals?

Contents

List of Abbreviations

AC	Alternating Current
BD	Breakdown
BDV	Breakdown Voltage
CB	Circuit Breaker
CT	Current Transformer
DC	Direct Current
EHV	Extra High Voltage
EMF	Electro-Magnetic-Force
ENS	Energy Not Supplied
ENTSO-E	European Network of Transmission System Owners for Electricity
FCP	Free Conducting Particles
GIS	Gas Insulated Switchgear
HVAC	High Voltage Alternating Current
HVDC	High Voltage Direct Current
IEEE	Institute of Electrical and Electronics Engineers
LC	Leakage Current
OHL	Overhead Lines
pC	picoCoulombs
PD	Partial Discharges
PDEV	Partial Discharge Extinction Voltage
PDIV	Partial Discharge Inception Voltage
RES	Renewable Energy Source

SF6	Sulphur Hexafluoride
TD	Tangent Delta
TIV	Tree Initiation Voltage
UHV	Ultra High Voltage
VLF	Very Low Frequency

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1 Introduction

The current transition from fossil fuel generated energy to renewable sources, combined with a shift in load consumption will drastically alter how we generate, transmit and consume power. An essential contributing factor in order to achieve the current energy shift and achieve the UN sustainable development goals [113] and the Paris Agreement [4] will be an optimal utilization of the electrical transmission system in order to facilitate the integration of renewable energy. The transmission system will both be required to implement new infrastructures suited to transmit renewable sources, mainly HVDC solutions, while simultaneously preserving its core structure by maintaining a system with significantly aged equipment.

A key part of ensuring the grid accomplishing current and future transmission demands is to prevent faults and premature ageing breakdown. Failures in the electrical distribution grid makes up for 90 percent of all power interruptions in the U.S [30]. In order to avoid insulation breakdown, monitoring techniques will need to be applied with regular frequency and with high quality.

The composition of the future grid will pose stability challenges, as the HVDC and HVAC needs to seamlessly cooperate without faults and instability, while simultaneously comply with an increased demand in overall transmission capacity. Another aspect seriously endangering the integrity of the transmission system is the predicted increase of extreme weather events [16] and how it will affect the grid both in terms of immediate harm and equipment ageing.

Historically there has been allocated considerable resources to researching the ageing mechanisms of high voltage equipment and implementing suitable monitoring techniques. However, the ageing mechanics of high voltage equipment and especially high voltage cables are still not fully understood [58], preventing accurate ageing modelling of high voltage equipment. The lack of knowledge is more evident in DC technology as it has been historically regarded as a specialist and niche field, thus being allocated far less attention. Hence there is a large dissonance between the current mass enrollment of HVDC technology and knowledge.

The transition from fossil fuels to renewable energy sources is already well underway, but is expected to still rise, and experts brand the coming decade as the decade of electrification [124]. The transition from fossil fuels to renewable will greatly increase our electricity consumption, with the total electricity consumption expected to increase by over 50% by 2040 [138]. Renewable power sources, namely hydro power and wind are already commercially viable, with other alternatives steadily edging closer to viability. A common denominator for renewable energy sources is their significant distance from load consumption, e.g far from population densities. This fits the properties of DC transmission due to superior performance over long distances [59]. Additionally a majority of renewable sources generate DC voltage. This combined with an increase in DC load consumption, predominantly by electrical vehicles, lies the foundation for a mass integration of HVDC. The mass integration of HVDC will both be seen in HCDC subsea cables connecting offshore wind and HVDC OHLs operating as a future backbone in intercontinental grids. The development varies globally, ranging from the U.S which trails behind to China who have conducted a mass enrollment and owns the majority of the ultra high voltage projects, effectively venturing into uncharted areas of the still undeveloped technology [105].

Another key aspect regarding climate change and sustainability will be the grids own emissions. The material historically utilized in high voltage installations have not been devoid of environmental concerns. One of the incentives for the transition from mass impregnated cables to polymer insulated cables was the concern of the environmental hazards of oil leak from aged cables [58]. Currently the main environmental hazard in the high voltage sector is SF6 , a highly electronegative fluoride gas with excellent insulating, arch quenching and cooling properties. As SF6 is the most potent greenhouse gas known to man [107], the industry is forced into drastic measures and is currently working on alternatives to replace SF6. Currently there are no alternatives gases available close to the properties SF6 offer.

As the field of electrical power engineering enters an era of major change and innovation, the field needs to evaluate which methods and technology requires revision, which should be vacated and which are the future. This paper will try to provide an overview of the current situation, as a state of the art review of high voltage monitoring will be provided. At the same time the paper will discuss the important role monitoring have towards achieving the UN Sustainability Goals.

2 Structure of the Report

The master thesis is structured in the following manner. Chapter 2 discusses the UN sustainability goals and how they influence the field of power transmission moving on-wards. Chapter 3 gives key insight in the mechanisms of breakdown in gas medium and solid state insulation. Chapter 4 covers the various types of high voltage underground cables, focusing on XLPE cables, AC vs DC, industry testing regime, costs and faults. Subsequently follows the main chapter, chapter 5, which aims to assess the various monitoring techniques applicable for cables, while also briefly discussing monitoring techniques for GIS and other items of plant. A discussion chapter will then ensue, assessing the current status of the monitoring techniques presented in the paper, while attempting to course out future monitoring trends and discuss the role high voltage has in ensuring progress towards the UN Sustainability Goals. Ultimately a conclusion is provided.

3 Sustainability Development Goals

The Sustainable Development Goals (SDGs) is an United Nations initiative established in 2015. The SDGs consist of 17 interlinked designated goals aiming to serve as a ”blueprint to achieve a better and more sustainable future for all”[113]. The seventeen SDGs are intended to be achieved by 2030, or rather within one generation. The SDGs are a direct successor of similar goals agreed upon by the UN members in the year 2000, known as the Millennium Development Goals (MDGs), which concluded in 2015. More on the outcome of the MDGs can be read in [134]. The 17 SDGs can at time be interchangeable and can all to various degrees be linked to the various aspects of society as they are all interconnected. There are however goals that can be directly linked to core parts of the societal structures, and additionally linked to specific causes and solutions. The electrical grid and the monitoring techniques ensuring optimal operating function, which remains the main topic of this paper, can be directly linked to numerous of the 17 SDGs. The following goals can be associated with electrical transmission:

- Goal 7: Affordable and clean energy
- Goal 9: Industry, innovation and infrastructure
- Goal 11: Sustained cities and communities
- Goal 12: Responsible consumption and production
- Goal 13: Climate action

3.1 Goal 7: Affordable and clean energy

As of 2019 90% of the global population had access to electricity, an increase from 83 percent in 2010. Of the total global electricity generation 25 percent where generated on renewable energy sources. [113]. In the transportation sector renewable made up for 3.4% of final consumption. The total global energy mix, not to be confused with electricity mix, consist of 17.1% renewables as of 2018. The European Commission are aiming to increase the renewable share of the energy mix to 40% by 2030[47], twice the amount of 2019. In order to accomplish the current goals of global electricity for all and a long term increase of renewable electricity, the investment, construction and improvement of the electrical grid will be essential. The techniques applied to monitor high voltage systems will need to emulate the overall rapid pace of the sector.

3.2 Goal 9: Industry, innovation and infrastructure

”For the global community to achieve Goal 9, industrialization, improvements in infrastructure, and the promotion of technological innovation by increasing investment in research and development are key.”[113]. A common theme in this paper will be the insufficient knowledge the field currently inhibits on the ageing of high voltage equipment. Despite continuous research the last couple of centuries and the allocation of substantial funding, the complex nature of high voltage equipment, especially in regards to cables, are still far from being sufficiently understood. The current mass shift towards renewable energy combined with a system nearing the end of its service time [131], e.g equipment installed in the 60-70s with an life expectancy of 50-60 years, will naturally be an incentive to allocate resources to further research. As the transition also requires the utilization of new technology or previously under utilized technology (HVDC), there will be a spur towards innovation within the sector. The race towards innovation within the sector will both generate jobs, economic growth, market share and industry influence. This can already be seen as China are way ahead of the curve in the enrollment of HVDC systems, and thus enjoys a large market share and industry influence since they effectively are the trendsetters. HVDC development will be further discussed in chapter 5.4.

The large enrollment of new infrastructure tasked to connect renewable energy to our electricity system will generate a large amount of new jobs. In the U.S it is estimated, granted investment between $12 and $16 billion per year through 2030 would generate 150 000 to 200 000 jobs annually [114]. Considering the typical pathways of HV lines and the remote nature of renewable energy sources, grid investment would result in the generation of jobs in high unemployment rural areas [137].

3.3 Goal 11: Sustained cities and communities

The large increase in global urbanization requires increased capacity feeding electricity to the large metropoles. This will require a stable and high capacity grid. The total electricity consumption is expected to increase by over 50% by 2040 [138]. Furthermore the load consumption will alter as there is mass integration of charging and battery solution into the regional and urban grid. For information on the outlook of battery solutions, see the EU Batstorm project [13] The existing predominantly AC grid will need upgrading and refurbishment, and furthermore an integration of primarily HVDC solution to facilitate the transmission of renewable energy sources.

Symbolically, one of the main threats endangering the stability of current and future power transmission which aims to contribute against the effects climate change, is climate change itself. Climate change will cause an increase in extreme weather [16], be it floods, heat waves, storms, wild fires and etc. The effect of global warming will also affect the transmission system. An increase in temperature will cause a decrease in transmission ampacity [45][42], e.g the maximum current that a conductor can carry without exceeding the conductors temperature rating.

Certain measures have historically been implemented to counteract the repercussions of weather induced fault. Especially in regards to moisture damage and lightning there have been implemented protection measures with large success, with the integration of cable jackets, surge arresters and overvoltage protection. The effect weather has on transmission lines, will understandably differ between OHLs, underground cables and subsea installations. For instance in Norway, 90 percent of temporary failures occuring in overheadlines will be weather induced [31].

The repercussion of extreme weather induced infrastructure damage is substantial, both economically and for grid supply and stability. The existing grid is designed to operate based on historical climate data and extreme weather induced faults have been considered as low probability events. Due to the rapid increase in extreme weather events, the existing grid is not designed adequately to cope and alterations in design are required. This issue have become conspicuous in the U.S, especially with the recent Texas Winter Storm of 2021 [35] causing major grid blackouts, highlighting the grids vulnerability to climate change. In the U.S extreme weather have been the cause of 78% of major power interruption in the period 1992-2010 [45]. A recent study have also showed that in the period from 2015-2020 there was a 60% increase of major grid blackouts, e.g exceeding 1 h duration and affecting a minimum of 50 000 people, due to extreme weather events in the U.S [125].

The European Network of Transmission System Operators for Electricity (ENTSO-E) keeps track of annual faults occurring in the Baltic and Nordic countries. In 2019 lightning and other environmental factors cause approximately 44% of all faults [101]. ENTSO operate with the term energy not supplied (ENS). This is a key parameter to track the overall supply stability of a transmission system. The combined ENS for the countries in the Nordic and Baltic have a stable and slightly decreasing trend over the last five years [101]. The ENS of the Nordic and Baltic countries can be seen in figure 3.1.

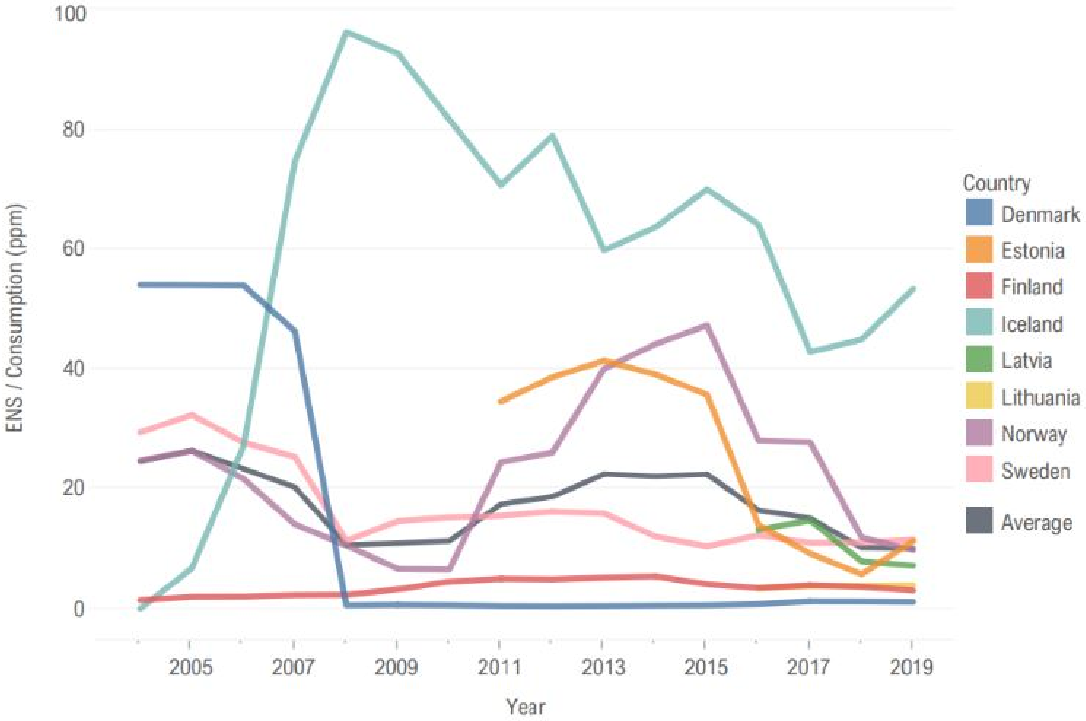


Figure 3.1: Energy not supplied in the Nordic and Baltic countries divided per consumption (ppm) in the period 2000-2019. [101]

Major blackouts will have direct consequences for a number of the SDGs as it invalidates key societal infrastructure such as sewage systems, water supply infrastructure, hospitals and etc. The economical cost of sufficiently upgrading the grid in order to cope with climate change is in the trillions of dollar range. However the possible economical repercussion if deciding to chose a reactive approach instead of proactive approach are far larger. A more in depth study assessment on grid resilience to extreme weather can be read at [82].

3.4 Goal 12: Responsible consumption and production

The amount of available potential renewable energy is not predominantly located within the confines of developed countries, as developing countries have large potential of renewable energy generation. There is however a large discrepancy in installed capacity between developed and developing countries, with the latter having approximately a quarter installed watt per capita compared to developed countries. [113]. Hence there are large grid installations projected within the next few decades in countries with either limited or non existing grid. Investment in quality grids and renewable energy solutions in developing countries will serve the interest of the UN, to mitigate the negative repercussions in emissions rates typically seen in countries experiencing economical growth. The projected grids in developing countries may serve as templates for new grid compositions, avoiding the challenges related to connecting new technology with aged and outdated systems.

3.5 Goal 13: Climate action

To accomplish the goals of the 2015 Paris Agreement [4] drastic measures are required. In order to accomplish the goals of the agreement, the global carbon dioxide emission will need to be reduced 45 % by 2030 and reach net zero emission by 2050 [113]. The total global emissions are complex, and consists not only of energy consumption. In 2017, energy consumption made up for 72% of the global Co2 emissions, with agriculture (11%), land use and forestry (6%), industry (6%), waste (3%) and bunker fuels (2.2%) making up the rest [54]. Hence the solution to global emission rates can not solely be based on electrification of the energy system, but the majority of solutions will still lie within this sector.

4 Breakdown mechanisms

The following chapter aims to cover breakdown and degradation of high voltage insulation for gas medium insulation and solid dielectric insulation. Gas based insulation traditionally includes air, SF6 gas and various other gas insulated systems (GIS). Solid dielectric insulation includes mainly modern polymeric construction and traditional paper based insulation.

Solid dielectric insulation breakdown mechanisms:

- Thermal breakdown
- Mechanical Breakdown
- Partial Discharges
- Instrinsic Breakdown

Gas based insulation breakdown mechanisms:

- Streamer breakdown
- Leader breakdown
- Corona stabilised breakdown
- Protrusion induced breakdown

The common denominator in all breakdowns, be it solid or gas based, is partial discharges. Partial discharges can be described as localised gaseous breakdowns that can occur in power systems if electric stresses are present. IEC 60270[67] offers the following definition of PD: “Localized electrical discharge that only partially bridges the insulation between conductors and which can or cannot occur adjacent to a conductor.” The localized breakdowns are either a result of an enhancement of the applied electric field or of a region of low breakdown field. Partial discharges is both a symptom of degradation and a cause of degradation itself [58]. The common stresses such as thermal, chemical and mechanical stress all generate partial discharge, which when first being present will be the main source of degradation in equipment and insulation material. PD activity results in the emission of heat, photons, acoustic waves as well as altering the chemical and physical composition of the insulation material. This combined with alteration of electrical parameters, makes the foundation for detectable values which is the field of PD monitoring.

Consequently partial discharges is delegated the most attention within the field, both presently and historically. Obtaining the correct understanding of partial discharge mechanics in the development stage, such as water trees and electric trees are vital, to halter and possibly prevent degradation.The principles of breakdown degradation in the two main types of insulation are at times often in theory analogous, but since gas medium insulation have more straight forward defined properties compared to liquids and solids dielectrics, the basic principles and theory will be discussed in the chapter covering gas, while the subsequent chapter aims to provide an overview of the particular cases of insulation degradation processes in solid state insulation.

4.1 Basic principles of breakdown mechanisms

This chapter aims to provide an overview of the basic principles of breakdown in gas medium, focusing on breakdown in air and SF6 gas. As mentioned gas breakdown mechanics, such a Streamer and Townsend, also occurs in liquid and solid dielectrics, but will be covered in this chapter, due to the complex nature of the other insulation mediums.

A breakdown process in power insulation can be defined as a sudden change in electrical properties, to the extent of changing from a galvanic isolation state to conductivity. Simply put, PD activity is the result of areas of reduced field strength in insulation, experiencing exceeding voltage levels, thus achieving partial discharge initiate voltage, abbreviated PDIV [58].

In air medium, a breakdown can be regarded as a collapse of dielectric strength between electrons. Common for all partial discharges, the applied electrical field have to exceed the critical field strength of the given gas medium and there must be a starter electron, also named seed electron with sufficient electric field strength to catalyst an electron avalanche. An example of this is the requirement to sufficiently energize a test cable in order to reach PDIV, e.g initiate a starter electron. The critical field strength can be defined as the limit where ionization is at zero. Exceeding values leads to positive rate of ionization.

Normally electrons are trapped inside the electrode, due to electrostatic forces, requiring access energy to detach itself and form negative ions. The required amount of energy is know as the work function [103]. The energy required to liberate a primary electron commonly originates from increased operating temperature, radiation, field emission and de-trapping of electrons present in insulation from previous PD activity [97]

Once liberated, the free electrons accelerate in the electrical field, colliding with neutral molecules, resulting in electron drift in the field direction. If these collisions provide a sufficient amount of energy, additionally electrons liberate, trailing behind positive ions, resulting in a cumulative process known as an electron avalanche. This process is known as the Townsend mechanism, which together with Streamer mechanism serves as the two main PD mechanisms.

The increased population of electrons and positive ions in the medium generates conductivity, but not necessarily immediate breakdown. Generated positive ions, with sufficient population, will further create additional electrical fields, which when supplemented to existing applied electrical field increase the further ionisation in a cumulative manner.

Electron avalanches generate ultra violet background radiation, which in place creates additional electrons in the field, contributing in a cumulative manner to increase conductivity, current density and heat, which all inevitably lead to discharge and breakdown. Townsend and streamer formation will shortly be discussed.

4.1.1 Townsend Mechanism

Townsend mechanism, also known as Townsend avalanche or discharge, is an electrical phenomenon in which free electrons, initiated by a starting electron, accelerate by the electrical field between the cathode and the anode, consequentially freeing additional electrons caused by a feedback process. The resulting electron avalanche generates conductivity in the insulation medium. The phenomena of electron avalanche can be contributed to the work of John Sealy Townsend [130].

The process, which begin by a starter electron. is initially in the phase of dark discharge Io, named based on the non glowing nature of the discharge phase .As the current of the discharge increases it reaches the point of self-sustained growth. The current increases further and the Townsend discharge becomes unstable, starting to emit a glow. The discharge is increasingly unstable rapidly increasing in voltage, before a sudden voltage drop, resulting in an electric arch appearing. The subsequent formula gives the current of a Townsend discharge:

$$I = Io\frac{e^{\alpha d}}{(1 - \gamma(e^{\alpha d} - 1)}$$

Where Io is the dark discharge current, d is the distance between anode and cathode, α is Townsends first coefficient and γ Townsends second coefficient. Townsends first coefficient provides the the number of secondary electrons produced by primary electron per unit path length. The second coefficient provides the average number of released from the cathode from a single positive ion.

Figure 4.1 shows the nature of a Townsend discharge from starter electron to arc over. It includes a voltage-current graph from a gas filled tube [85].

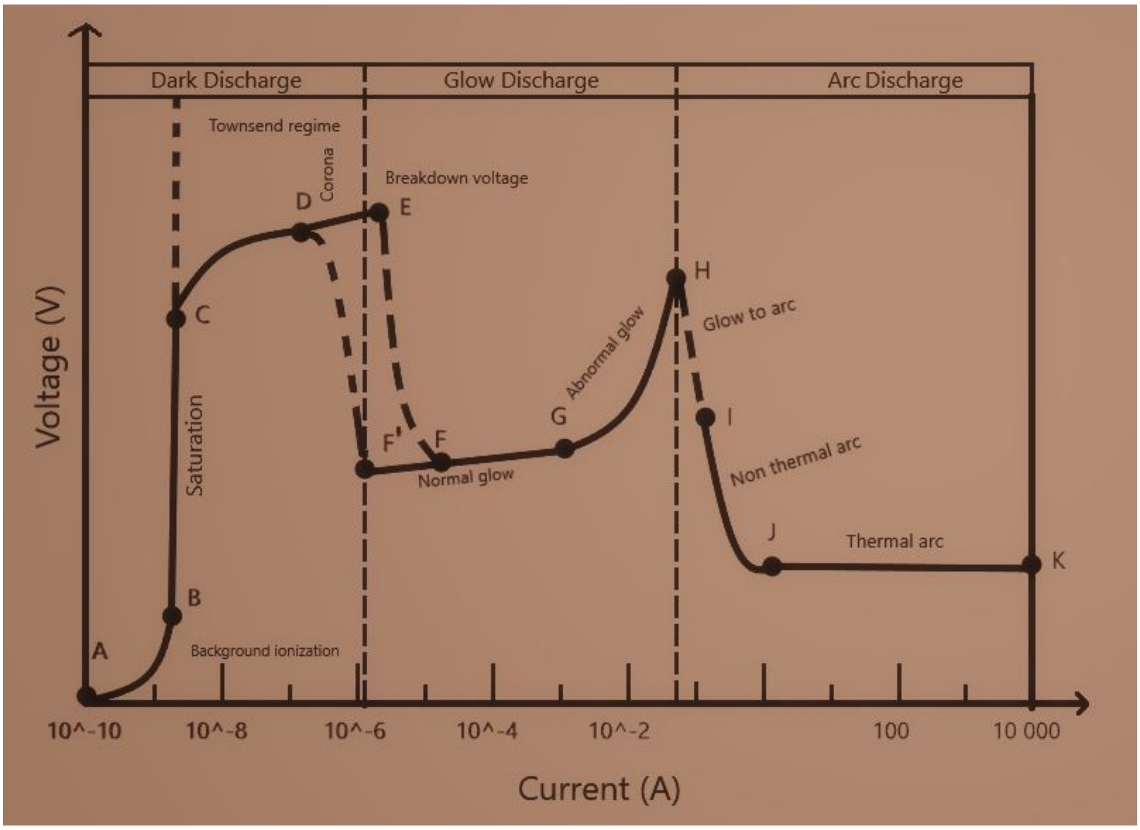


Figure 4.1: Voltage-current characteristics for a Townsend Discharge in gas medium[85].

The criteria for Townend induced air breakdown is given as:

$$1{-}\gamma(e^{\alpha d}{-}1) = 0$$

$$\gamma(e^{\alpha d}{-}1) = 1$$

$$\gamma(e^{\alpha d} = 1$$

This gives the three possible conditions:

A:$\gamma e^{\alpha d}$ < 1

B:$\gamma e^{\alpha d}$ = 1

C:$\gamma e^{\alpha d}$ > 1

A: The current will not be self sustained. B: The value is sufficient to release a secondary ion, but not to initiate avalanches in a cumulative manner, is also know as treshold sparking condition. C: The ionization process is cumulative, with avalanche generation. In theory the ionization in this condition would be infinite, but will be limited by the eventual voltage drop in the arc. The conditions to be fulfilled in order to initiate a Townsend avalanche is an existing free electron, seed electron, to be ionized within a significant electrical field.

The required free electron can be obtained within the gas medium by ionization radiation, thus creating a ion pair. While the positive ion travels towards the cathode, the free electron gravitates in the opposite direction towards the anode. If sufficiently energized by the field, the electron may collide with gas molecules, thus liberating additional free electrons, this is known as the feedback process. This process is cumulative as the growing amount of electrons accelerates within the field, thus creating an electron avalanche. The multiplication (M) and growth of the avalanche population would in theory be infinite, but is physically limited due to the space charge of electrical field, the limit is known as the Raether Limit [109]. When a sufficient avalanche population occurs in the medium, the gas becomes conductive and breakthrough occurs.

4.1.2 Streamer formation

Streamer leaders, or streamer discharge, is an electrical phenomenon occurring as a direct result of Townsend discharges (avalanches) trailing behind ions, generating space charge within the field in close proximity of the original avalanche [93]. Figure 4.2 shows the formation of streamers near an electrode rod [58]. A illustrates avalanche growth, b/c streamer initiation and d/e streamer growth

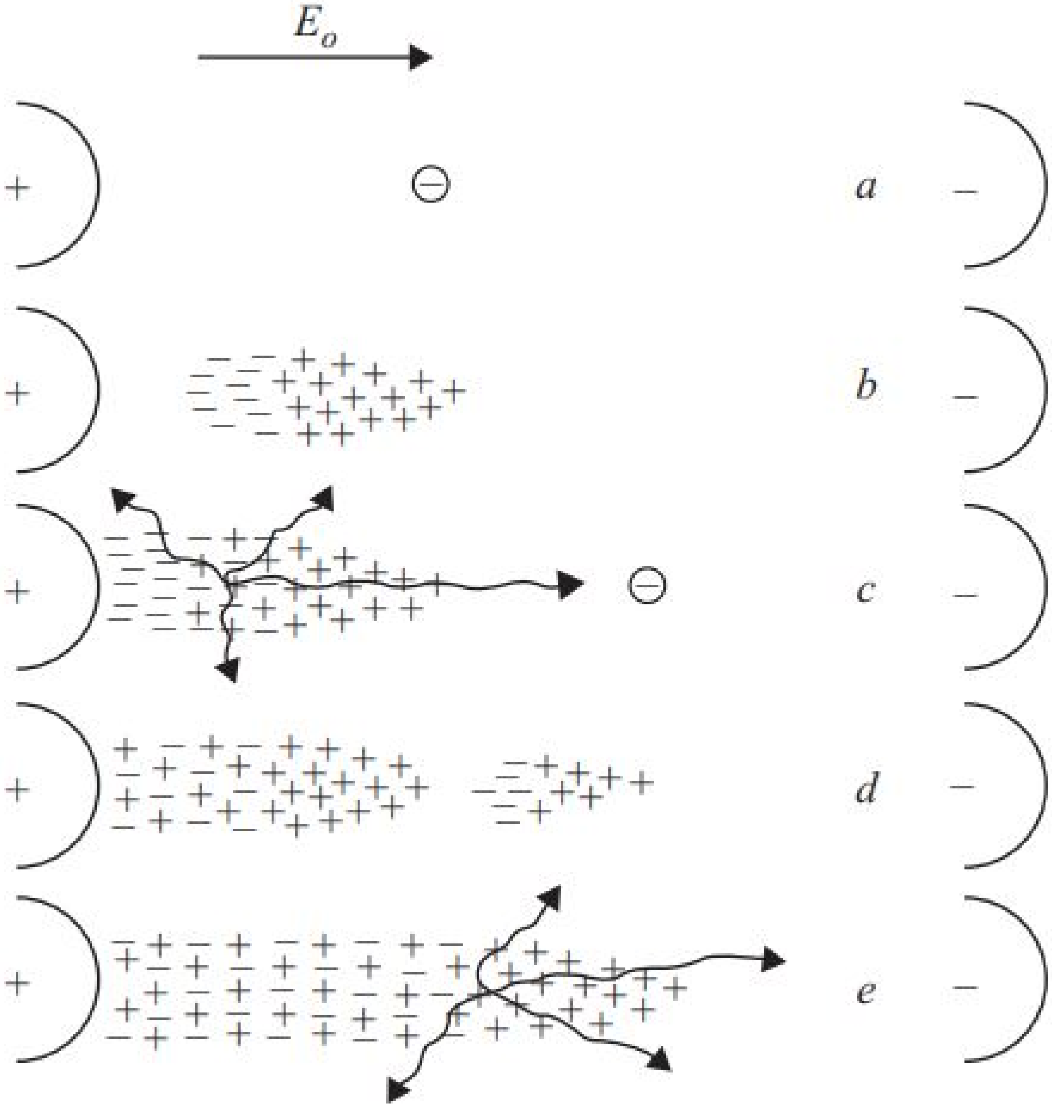


Figure 4.2: Positive streamer formation near electrode gap [58]

As the initial Townsend avalanche reaches an electron population of 10^6 to 10^8 electrons, it will leave behind immobile ions at its tail, whilst electrons accelerates to the avalanche head. The immobile ions at the avalanche tail leads to space charge building up in the area. The space charge itself generates new electrical fields in addition to the already existing background field.

Thus, areas of the gap will get increased field strength, which creates additional avalanches, often illustrated as ”trailing” behind the original Townsend discharge. the phenomenon is self-propagating and will eventually lead to the avalanches ”closing” or ”filling the gap”, creating a line of high conductivity, typically seen as arch overs.

4.2 Gas insulated breakdown mechanisms

Gas insulation can be defined as gaseous medium tasked to insulate current conducting material. The two main commercially viable gas solutions utilized as insulation is air and SF6 gas. Conveniently air has eminent insulation properties (at sea level), providing a healthy baseline for all gas based insulation. However sulphur hexafluoride, SF6, has far superior properties and is traditionally the preferred option, especially in advanced enclosed systems, ranging from transformers, gas insulated cables (GIS), switchgear, substations and gas insulated lines (GIL). Since air insulation is a cost free alternative, it is utilized in a large amount of installations and is applied where there is deemed low safety risks. The prime example of air insulation is OHLs.

The main strengths of SF6 is its high dielectric strength, heat characteristics, non flammable, high density, and a high withstand capacity due to it being a hypervalent gas. Compared to air it has five approximately five times the density, three times the amount of heat capacity, twice the amount of heat transfer and importantly about three times the dielectric strength [92]. These properties makes SF6 an excellent gas for electrical insulation and electrical switching.The three main functions of SF6 in electrical operation is electrical insulation, arch quenching and cooling [58] [5].

As mentioned, SF6 is a hypervalent gas, meaning being highly electronegative. The electronegativity actively negates ionization avalanching by electrons moving within the field, which if colliding with neutral molecules, can attach itself, resulting in the creation of negative ions. These negative ions are unable to cause ionization in the field, effectively stealing free electrons from potentially enhancing avalanche processes. This relationship, that we could regard as net ionization, is determined by the attachment coefficient n and the ionization coefficient a [58].

The ionization coefficient a is given by:

$$\frac{\alpha}{p} = f1\frac{E}{p}$$

The attachment coefficient n is given by:

$$\frac{\eta}{p} = f2\frac{E}{p}$$

Where E is the applied field and p is the gas pressure. If ionization dominates the rate of attachment cumulative ionization is possible, e.g ionization avalanche. Contrarily if the attachment dominates the rate of ionization, it will inhibit the growth of discharges.

Although highly electronegative, there are gases available with higher electronegativity, e.g higher dielectric strength [29]. These are shown in table 4.1.

Gas	Relative Dielectric strength	Classification
H2	0.18	Non-attaching
Air	0.3	
Co2	0.3	Weakly attaching
CO	0.4	
C2F8	0.9	
CCl2F2	0.9	
SF6	1.0	Strongly or very strongly attaching
C-C4F8	1.3	
C-C4F6	1.7	
C4F6	2.3	

Table 4.1: Dielectric strength of certain gases relative to SF6. [29]

The mentioned properties give along with other factors, in especial the fact of SF6 installations being enclosed systems, the following advantages: Reduced fire risk, overall increased component safety, inferior construction footprint [5]. As SF6 has a significantly higher density than air, the power equipment can be more compact, effectively taking less space in nature, making it a favourable option in urban environments. Nonetheless SF6 gas has two major disadvantages compared to air, which in turn have mandated a substantial amount of attention and studies from the industry. SF6 has major environmental concerns and is considered to be brittle.

SF6 is an extremely potent greenhouse gas, with a global warming-potential, GWP, of approximately 23 900 times greater than the equivalent mass of CO2, the most potent man known GHG gas in the world. It has an atmospheric residence of 650 to 3,200 years [48]. Global emission models estimate the SF6 emission of 2018 to be that of 373 k tonnes CO2-e in 2018 [36]. Since the first measurements of SF6 emissions in 1995, the values have steadily increased from the initial measurements of 3.5 ppt to 10.5 ppt [126]. Considering the fact that 80 % of all produced SF6 is utilized in the electric power system [33], it is beyond any doubt that the field of high voltage transmission carries an important responsibility in the desired goal of global warming reduction.

Despite being commercially used since the 1960s in power equipment, when SF6 replaced polychlorinated biphenyls (PCBs) due to harmful bi product of dioxins, the potency and risk of the gas was not truly discovered until it was mentioned in the Kyoto protocol of 1997 [107]. Even then the industry, perhaps willfully, did not take a stance on the potential harmful continued use of SF6 until a considerable amount of time passed.

Today a broad majority of the industry realizes that a necessary shift from SF6 to new commercially viable gas insulation is inevitable. However this poses a challenge with great difficulty, as there currently is no commercially viable gas alternative which can compete with the performance of SF6. Alternative gases may have single properties better suited than SF6, as illustrated in table 4.1, but lack the overall excellent properties SF6 offers. As previously mentioned, the three main tasks SF6 free solutions will have to accomplish are insulating, arch quenching and cooling. An SF6 alternative should have acceptable performance in these operations to be viable.

A large population of already installed GIS construction utilize SF6 gas. These installations are standardized with the current power system, and most have a substantial remaining life time in service [129]. Replacing highly functional installations, with potentially inferior alternatives, with remaining long expected life expectancy will be a costly and a circumstantial operation. An initial counter argument against out-phasing SF6 is the fact that SF6 gas, although extremely potent, must leak to have a global house warming effect. Thus the proposed solution instead lies in prevention of potential leakage by upgrading preexisting installations. The documentation of the actual amount of leakage is however limited, but reported leakage is suspected to be substantially lower than actual numbers. Enhancing the leak prevention techniques would drastically reduce future emissions. A large amount of classical and aged SF6 installations have already been replaced. Newer installations have lower quantities of SF6 and experience lower emission rates.

Zero leakage, achieved by improving current SF6 systems. is however an impossible task. A German analysis study showed that the leakage will despite improvement in gas leakage prevention increase due to enlarging population of SF6 based plant items due to the ongoing electrification of the energy system, hence only a transition to non SF6 applications will lead to a decrease in emissions [143] . The analysis is based on German data and predictions, and handles two scenarios. The first being a continued focus on gas leakage prevention, and the second scenario being a transition to SF6 free technology. The second scenario is based on the current estimations on when commercially viable SF6 free installations are accessible. On the other hand the first scenario is based on more accurate data, since the current state of the art SF6 installations in terms of SF6 emissions are considered a mature technology by the power industry, with limited improvements expected.

The German analysis will act as a representative model for the western power systems, an urbanized country traditionally depended on non-renewable energy currently undergoing a power transition to renewables. The following figure 4.3, include the models presented in the study, presenting the two scenarios both with the year specific SF6 stock and the annual emission. Both models utilize the 1960-2100 range. Colours represent the SF6 technology and their estimated percentage emission. It should be emphasised that the models, especially for scenario number two, include uncertainties as they are based on the predictions of future technology.

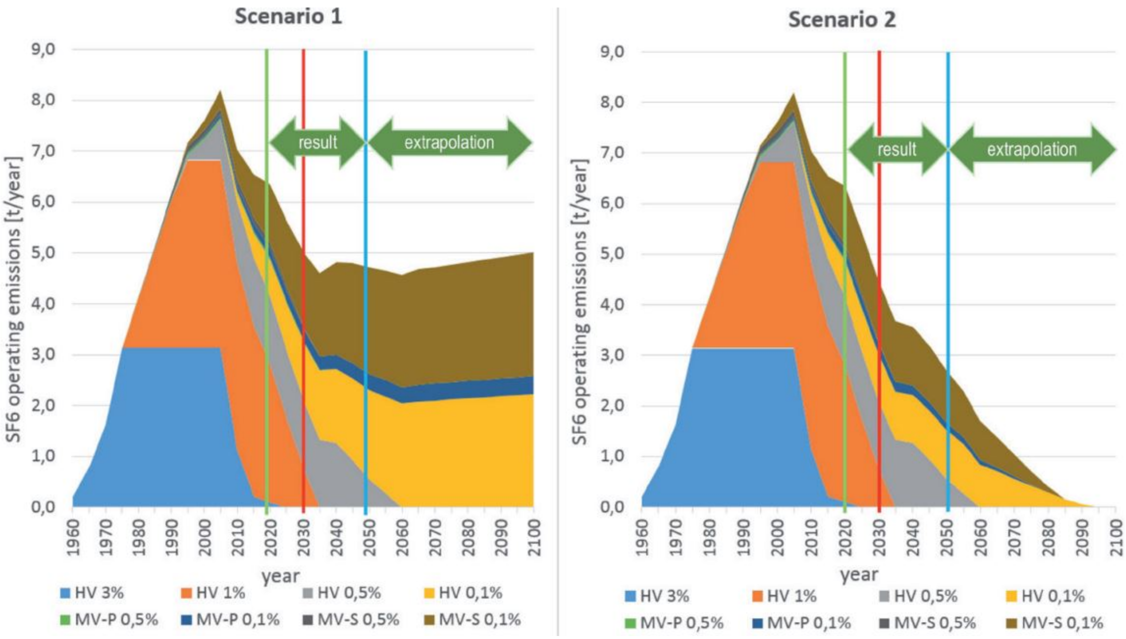


Figure 4.3: Expected SF6 emission in Germany scenario 1 and 2 [143].

Christian M. Franck, Alise Chachereau, and Juriy Pachin from the High Voltage Laboratory, ETH Zurich, Switzerland goes in great depth discussing the state of the art of SF6 alternatives and future trends [51]. The paper highlights the difference between SF6 alternatives in medium voltage and high voltage switchgear. There is larger difficulties in finding suitable alternatives to HV switchgear were only gas can be utilized, unlike for MV switchgear where liquid and solid insulation can be utilized in combination with gas alternatives. The paper also points towards the utilization of mixtures between fluorinated gases and high volatile gases as a SF6 alternative with suitable properties. It should also be emphasised that a transition from conventional SF6 methods to other alternatives would result alteration in size due to altered density properties, further complicating the eventual transition.

There is however currently broad political agreement on the out-phasing of SF6 gas. The European Union Commission in October of 2020 issued a report [44] outlining SF6 as one the main GW perpetrators, clearly indicating a plan of out-phasing SF6. The EU has also issued the Regulation (EU) 517/2014 [118], aiming to cut the emission of F-gases by two thirds in 2030 relative to 2014. This goal will be tried fulfilled by regulating sales, limiting new SF6 installations and enhancing current prevention methods. Another notable plan for out phasing SF6 can be found in California, where the California Air Resources Board (CARB), commissioned a draft discussing a proposed out-phase [18]

To summarize, there seems to be a broad consensus on out-phasing SF6 and in the meantime to reduce emissions by stronger regulations and prevention methods, while awaiting for commercially viable alternatives. Alternative gas solutions are edging ever closer to viability and are already utilized in some types of equipment.

4.2.1 Breakdown mechanisms

Secondly, SF6 is, despite being a superior insulator, regarded as ”brittle”, meaning that when faults first occur, albeit rarely, the ionization processes that leads to breakdown occur at a much swifter pace than in air medium. Additionally the extent of damage in GIS due to breakdown is magnitudes higher, leading to substantial repairment.

The breakdown mechanisms of SF6 and other gas mixtures utilized in GIS are discussed in detail by N. H. M.lalik and A. H. Qureshi [92]. The limit, or breaking point before ionization breakdown occurs. is known as the critical reduced field strength: a-n = 0. The reduced critical field strength for SF6 and air respectively is 89kV/cm and 27kV, meaning SF6 has a dielectric capacity approximately three times as high as air [58]. However, when the limit is reached for SF6, the ionization and imminent breakdown generates with high acceleration in a linear curve resulting in breakdown of the insulation medium. The rate of ionization after the critical field strength for air and SF6 is shown in figure 4.4. Therefore monitoring and prevention techniques of reduced field strength, albeit rare, are the focal points of SF6 technology prioritization. It should also be noted that the repair costs and repair time are significant for SF6 installations.

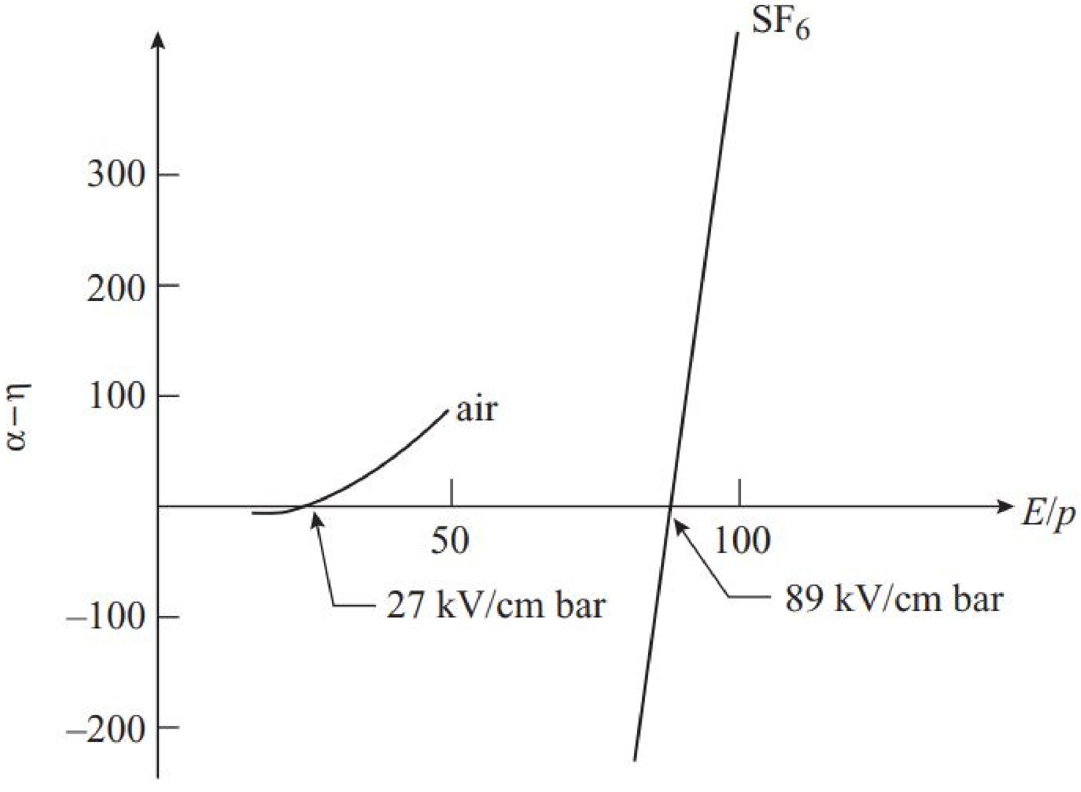


Figure 4.4: Effective ionisation coefficients in air and SF6 [58]

Factors influencing reduced field strength in GIS applications are the following:

- Voids in insulation: Rarely found in GIS applications as they are effectively being detected during factory tests.
- Protrusions: Usually forms due to improper craftmanshift. Can either occur in the chamber enclosure or in the conductor.
- Particles in insulation: This is the most critical condition. Especially the presence of metallic particles can be detrimental to breakdown strength. [142]

Table 4.2 provides relevant characteristics on defects found in GIS applications [14][117]

Defect type	Length[mm]	Apparent charge[pC]	Detectable length of defect at Un [mm]
Moving particle	3-5	2-10	3-5
Protrusion on HV conductor	approx 1	1-2	3-4
Protrusion on enclosure	4-6	2	10-15
Particle on insulation	1-2	approx 0.5	3-10
Void	3-4	1-2	2-3

Table 4.2: Defect characteristics[29].

The effect of surface roughness, protrusions, metalic contaminants will decrease the breakdown strength. During the installation procedure of GIS applications, ensuring clean surfaces and the absence of FCPs are vital. Most GIS applications are designed so that in ideal conditions the maximum applied field across the installation won't exceed 40% of the theoretically critical limit of 89kV/cm [5]. The theoretical critical field strength of SF6 and other GIS applications will however not be withheld in manufactured equipment. The extent of surface smoothness required is impossible to manufacture and impurities and roughness is inevitable. Monitoring and prevention techniques will be discussed in chapter 6.10.

4.3 Solid dielectric insulation breakdown mechanisms

Breakdown in insulation can be defined as the moment where the local dielectric stress exceeds the local dielectric strength. Ideally with newly manufactured insulation the local dielectric strength will not be exceeded by nominal operating voltages. There is however a wide range of stressing mechanisms occurring due to manufacturing or operating conditions, significantly increasing the probability of failure. The probability of failure for a given cable is given by:

$$P_f = 1 - e^{\frac{E^{\beta}}{\alpha}}$$

Where P_f is the probability of failure, E the electrical field strength, β is the Weibull shape parameters for the test and α the Weibull breakdown strength to the given test cable length [24].

The following mechanisms are central to electrical stresses exceeding local field strength and subsequent, accelerated ageing:

- Thermal stressing: Overheating of cable due to accessories defects and operating conditions
- Wet environment: Presence of water increasing the local electrical stress.
- Alteration of physical components: Corroded neutralsm, shield misalignment.
- Chemical alteration: Typically oil leakage or migration in oil fluid paper cables or oil leakage from associated power system accessories.
- Poor manufacturing: Impurities, cavities, sharp metal protrusion, shield imperfections etc.
- Poor craftsmanship: Cuts from splicing, material contamination, insufficient installation, misaligned or poorly connected equipment.

Typical faults occurring in solid state insulation, in this case an extruded cable, can be seen in figure 4.5.

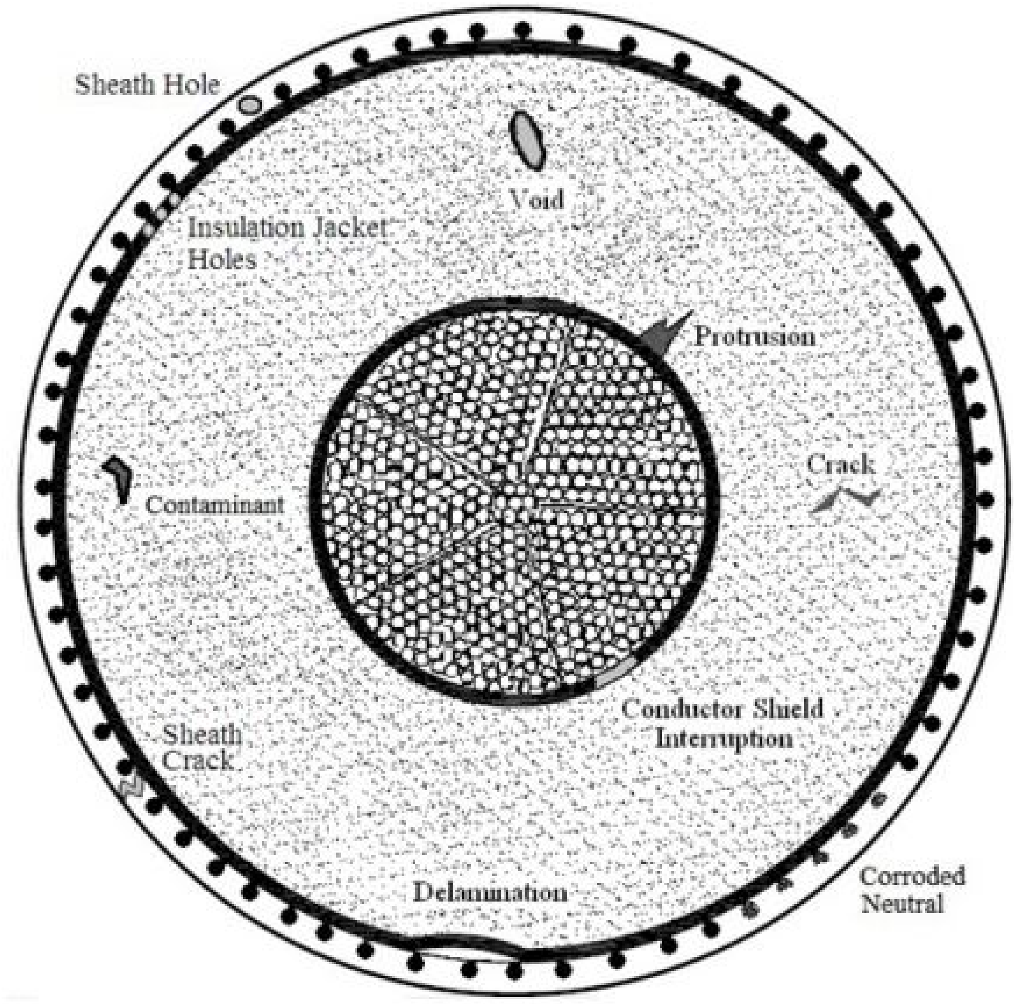


Figure 4.5: Typical cable faults in an extruded cable [25]

Solid dielectrics can be defined as solid material compositions designated to insulate current conducting material. The most common types are cable insulation and insulators, with material utilized including glass, porcelain, paper and synthetic polymers. The importance of degradation prevention and monitoring is regarded as larger for solid based insulation, than gas based, since when breakdown first occurs, the solid material is permanently deteriorated, while the gas based insulation will partially recover if one applies the appropriate electrical field [58].

The properties of paper based insulation and extruded cables will statistically vary.This will also be the case for the same types of cable. They have different material composition, different production conditions, contamination, defects, voids, and aging. The breakdown strength will, in these cases, have strong statistical dispersion, and the breakdown values will vary. In the instance of non-ideal material structures such as impurities, the breakdown strength is significantly reduced, emphasising the importance of quality manufacturing. Monitoring and predicting life cycles of solid dielectric insulation is challenging due to large statistic variations, and the unique operating stress each installations experience during a lifetime of service.

4.3.1 Partial discharges

IEE 400.3 defines partial discharge in solid insulation as: ”An electrical discharge that only partially bridges the insulation between conductors. A transient gaseous ionization occurs in an insulation system when the electric stress exceeds a critical value, and this ionization produces partial discharges” [70]. Once present, PDs will be the leading cause of escalation of degradation stresses and will drastically reduce the lifetime of insulation[58]. PDs occurs in insulation defects, at insulation surfaces or in the case of gas insulation, in homogeneous fields in the electrical field, e.g impurities like metallic objects. These make up three types of PD: Internal discharge, Surface discharge and Corona discharge, which will be discussed subsequently.

PDs manifest themselves as sparks, with less than 1us duration. The discharge results in the emission of heat, light, acoustic waves, chemical alteration and electromagnetic pulse. Although small in size, PDs in a cumulative manner will damage surrounding insulation material, this is know as electrical trees.

In solid dielectrics these conditions apply to generation of PD activity. A) An enhanced electrical field either internally or on the surface, e.g overvoltages. B) Areas of reduced field strength, e.g defect in the insulation. If the voltage of the applied field exceeds the critical field strength of specific areas of the insulation, PDs will occur. This is known as the partial discharge inition voltage (PDIV). In other terms, for partial discharges to occur, there need to be impurities and weakness present within the insulation and sufficient voltage present. Defects in insulation can be the following: Cavities within the insulation, protrusions, impurities and physical abrasions of the material.

When these weaknesses in the insulation are present, the applied electrical field will also apply to these cavities and protrusions. This generates high levels of electrical stress in these small areas which in turn easily will exceed the breakdown strength of the insulation material. In the case of cavities, preliminary stress from prior PD activity will lie dormant in the walls of the cavity, further decreasing the breakdown strength of the area. PDs wil not immediate lead to conductivity and breakdown, but will inevitably with increased population over time lead to insulation breakdown. As solid state insulation is incapable of self-recovering, monitoring techniques and quality of manufacturing are deemed to be the only solutions to extend solid state insulation quality and lifetime expectancy.

4.3.2 Type of discharges

Solid state partial discharges can be classified into four groups:

- Internal discharges
- Surface discharges
- Electrical treeing
- Water treeing

Void and defects

As discussed above, cavities, protrusions and voids caused by manufacturing and ageing are the principal culprit of partial discharge in insulation, because the relative breakdown strength of the voids is relative high compared to surrounding insulation. The geometry and size of the void determines the breakdown strength. For example, sphere shaped voids have the lowest relative strength compared to insulation, while other shapes have higher values. The size of the voids also factors in, with larger voids significantly reduces the breakdown strength and increases the probability of breakdown. The relation between void attributes and breakdown strength is further described in the Paschen law and Paschen curve, illustrated in figure 4.6.

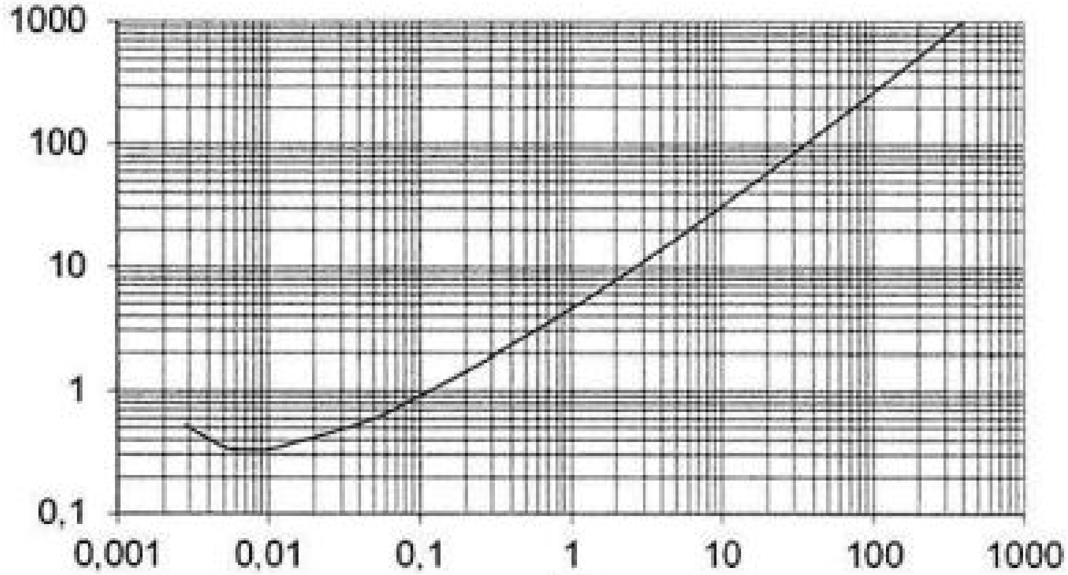


Figure 4.6: Paschens curve for air [60]

The Paschen law describes the breakdown voltage of gas as function of pressure and gap length [8]

Internal discharges

As its the name suggest, internal discharges occur within the solid state insulation material. As unavoidably impurities and defects caused by aging and insufficient manufacturing are present in any given insulation, localized spaces and impurities will experience high electrical stress as high voltage is applied. These spaces, or defects if you will, has a significantly lower breakdown strength than its surrounding material, and thus will reach breakthrough in normal operating voltage range, resulting in the generation of discharge. These spaces/cavities will have the breakdown strength of air at 8.9 kV . The partial discharges can occur both tangential and perpendicular to the field, meaning diverging the field or moving at a right 90 degree angle to the applied field.

The discharge then generates heat, electromagnetic radiations, and will in time enlarge in size, generating electrical trees. As previously mentioned initial partial discharges will not cause immediate breakdown, but over time a growing population of discharges will ”bridge” and cause complete breakdown of the insulation. The relation between the severity and number of defects with the probability of breakdown is evident. However there is significant statistical variation between types of defects.

It should also be noted that the size of the defect is not the sole parameter deciding breakdown strength, with also the composition of gas present being a deciding factor. PDIV values will have diverging values within the same insulation material, and also statistical variations between different cable types. For example a spherical void within a XLPE cable will have three times the PDIV value as a similar identical defect with the same conditions in an EPR cable. Granted defects within the same insulation, the following aspects determine PDIV: Size of void, shape, proximity to surfaces, and alignment with applied electrical stress. Table 4.3 and 4.4 shows electrical stress present in XLPE and EPR cables for different shapes of voids and position within the insulation [70]. Statistical data on the defects in solid state insulation is an essential part of high voltage monitoring. Granted sufficient inspection of a manufactured cable, the present defects combined with corresponding defect values, will with acceptable accuracy asses the current and short termed future of the cable health. Given the complex nature of operating conditions, unpredictability will occurs, thus frequent quality testing will be required. The complex nature of defects in solid state insulation is an extensive field, which exceeds the scope of this paper. For further read, the following paper goes in depth on defects[70].

Cavity shape	Eletric stress in cavity	Cavity at conductor shield	Cavity in middle of insulation	Cavity at insulation shield
Spherical	1.23Ed	11.7	13.8	16.0
Flat longitudinal	2.3Ed	6.3	7.4	8.6
Flat radial	Ed	14.0	17.0	20.0

Table 4.3: PDIV in kV for 0.5 mm (20mill) cavity in XLPE [70]

Cavity shape	Eletric stress in cavity	Cavity at conductor shield	Cavity in middle of insulation	Cavity at insulation shield
Spherical	1.31Ed	11.0	13.0	15.0
Flat longitudinal	3.3Ed	4.1	4.8	5.6
Flat radial	Ed	14.0	17.0	20.0

Table 4.4: PDIV in kV for 0.5 mm (20mill) cavity in EPR [70]

Surface discharges

Surface discharge manifests at the confines of the insulation, in the form of electric streamers [50]. Typical locations for surface discharges are terminations and accessories. In short the streamers occur due to electrical field enhancement, manufacturer faults, poor accessories connections and contaminations leaked to the surface. Initially the concept of surface discharge is the same as internal discharge, but the main difference is that the partial discharges significantly move tangential with the applied field. The discharge is characterized as low amplitude, but has a high discharge rate. In terms of deterioration, surface discharge is proportionate to internal discharges, despite its higher discharge area.

The following conditions may lead to surface discharges:

- Contaminations leaking to the surface. Typically water moisture.
- Physical abrasions due to splicing the cable
- Installation faults. Poorly connected terminators, accessories and neutral.
- Improper shrinkage of accessories

Cable systems will as with internal discharges experience surface discharges as a result of ageing, e.g contamination leakage. There is however a much larger influence of human error in regards to surface discharges, as the majority of causes are related to manufacturing and installation. However these discharges are not deemed as critical to overall cable system health as internal discharges, since it rarely leads to actual cable failure. It is also relatively easier to repair and detect. Similar to internal discharges, substantial enhancements in cable health can be achieved by improving the manufacturing quality. For more on surface discharges see [49].

Corona Discharge

Cornona discharge is discharges occurring in gas insulated installations, such as SF6 and other GIS constructions. Corona discharge in air installations is a well known phenomenon, and should be briefly discussed due to its potential usage in power installations. The inception voltage of air discharge is given by the following relation:

$$\frac{E}{N}$$

Where E i stands for the electric field (E V/cm) and N for the gas density moles/cm. Studies have examined the relation between breakdown discharge inception voltage and air density and found that the inception voltage decreased approximately linearly with air density [32]. Operating power electronics in low density air will thus be delicate.

The most notable example of low density operating conditions are in aeroplanes, or switchgear installtions situated in high elevation areas.

In GIS applications, granted a uniform homogeneous field, breakdown will normally not occur, especially when considering the applied voltage is design to not exceed 40% above the critical field strength of the gas medium. In-homogeneous field does however occur. Impurities and protrusions within the metal enclosed system, e.g object such as sharp metallic points, have higher dielectric constant or conductivity, than the surrounding gas medium. These impurities may be present because of manufactural defects, but could be a a result of operating actions such as closing and opening the circuit. The particles present in the medium normally clusters near the electrode and at the basin of the containment. Corona discharge may lead to the development of PD and will lead to a significant reduction in critical field strength of the insulation. Corona generation may also be present if the given enclosure contains bolts and other metallic parts. Corona discharge will interfere with PD signals in both electrical detection and acoustic detection.

Electrical treeing

Electrical discharge, as found in cavities and voids, work in a cumulative manner, in that they with sufficient energy further release additional electrons, which in turn generate electroluminescence, ultraviolet rays and photon bombardment. In other terms amplify the discharge process. If, and often when amplified, the now stronger discharge may bombard the surrounding material with particles and over time initiate deterioration on a chemical level, creating pathways through the insulation. If the pathway leads to areas of high electric stress, such as contaminates, the bombardment process is further amplified. IEEE defines electrical treeing in this way: ”Tree-like growths consisting of non-solid or carbonized micro-channels, which can occur at electric field enhancements such as protrusions, contaminants, voids, or water trees subjected to” [1].

The deterioration pathway is reminiscent of tree shapes, hence the name electrical trees. The pathways of the trees, or if you will the branches, are understood to follow along the lines of local electric fields. Unfortunately electric trees, if developed, have as of now no remedies, and cables diagnosed with electric trees will be regarded as terminally ill.The life expectancy of ”terminally ill” cables can however be significantly extended by the use of additives. [140]

The use of additives have been researched for approximately 40 years. The method consists of mixing additives with the polymer insulation with the intention of achieving the highest possible tree initiation voltage (TIV). Certain additives have properties suitable for suppressing electrical treeing mechanisms. For example UVA and UVB are excellent absorbers of ultra violet rays [78], significantly contributing to the suppression of tree growth.

Considering the seemingly unattainable ideal of constructing polymer cables void of defects, the chemical alteration route, which addatives represent, emerges as the most reasonable solution in terms of strengthening the electrical and chemical properties of the cable.

Water treeing

IEEE defines water treeing as the following: ”A tree-shaped collection of water-filled micro voids that are connected by oxidized tracks. Water trees can occur at electrical field enhancements such as protrusions, contaminants, or voids in polymeric materials subjected to electrical stress in the presence of water”[1]. In traditional polymer cable manufacturing the potential negative consequences of water ramification were seen as a non-issue, and no specific countermeasures were initially applied. As time passed a significant amount of polymer insulated cables experienced unexpected breakdowns [121], which after examination was ruled as due to water treeing.

Water trees initiate at the presence of water, and grow through the insulation in tree shaped manners, and may in some cases lead to cable breakdown. Since water has a significantly higher dielectric constant compared to the surrounding insulation material (80 compared to 2.5-3.5 for XLPE), the presence of water results in a drastic rise of conductivity. The probability of failure increases with water tree length. Unlike electrical trees, water trees grows significantly slow and proves challenging to detect due to the microscopic size of the branching pathways. If the tree dries out, detection of the tree will become impossible. If first occurring, the deterioration is permanent [112]. While electric trees resemble the typical tree shape, water trees are more erratic in structure, and carry more of a bush like structure.

Water treeing is divided into two main groups, vented trees and bow tie trees. Vented trees originate from the surface of the polymer insulation and may breach across the insulation proper seriously harming the insulation, with potential breakdown as result. Bow tie trees originate from voids containing water, and is regarded as less severe than vented trees, due to it’s limited range of branching, not breaching across the insulation, and even in some cases branching ceasing to continue growth. A bow tie water tree can be seen in figure 4.7. Examinations have displayed the phenomena of electrical trees branching through already preexisting water trees [58].

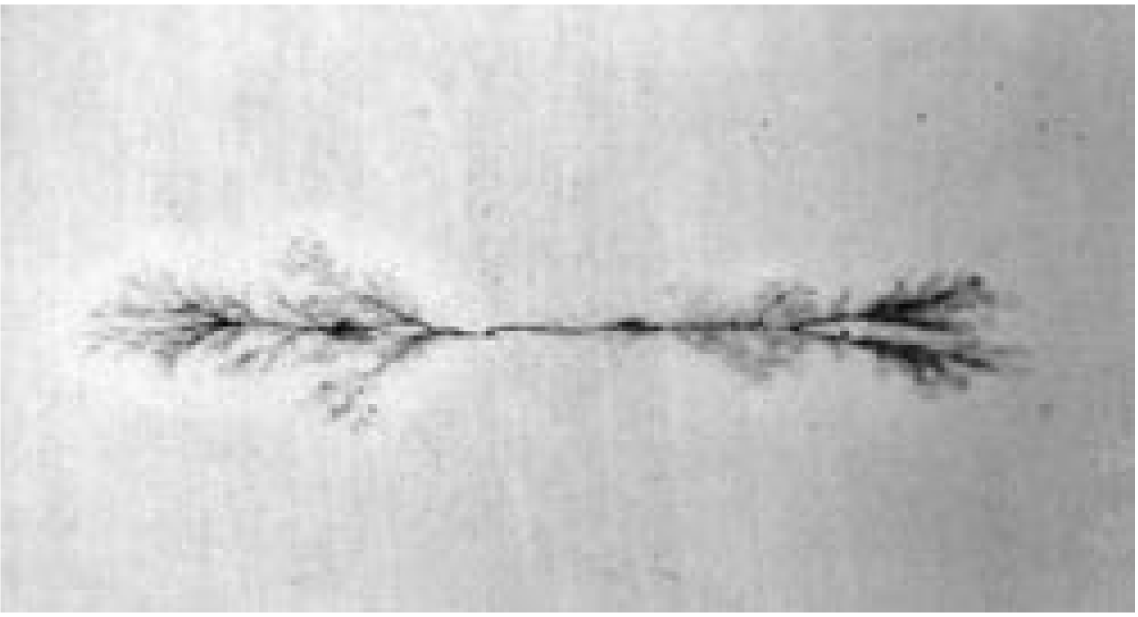


Figure 4.7: Bow tie water tree [39]

Recently it has been showed that the use of surfactants, in particular GMS and SDA, have been able to suppress the propagation of water trees in polymer cables, by absorbing water molecules, effectively reducing the amount of water molecules protruding deep into the insulation [119].A study of 2020 also suggested that in addition to absorbing the water molecules, the use of surfactants also attracts the water molecules via polar interactions, further reducing generation of water treeing.[78]. This can be seen in figure 4.8

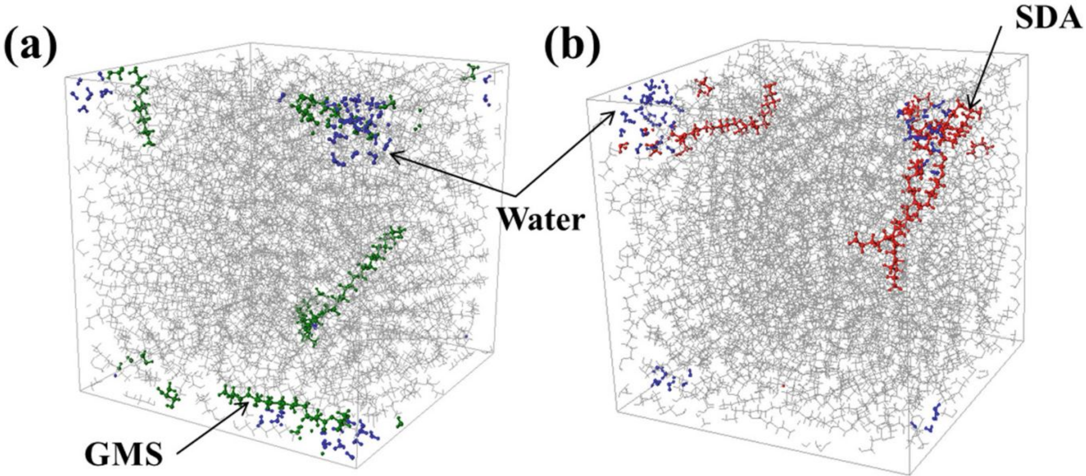


Figure 4.8: Surfactant attracting and absorbing water molecules in polymer insulation. (a)GMS (b) SDA

[78]

4.3.3 Operating Conditions

The aforementioned mechanisms, all related to partial discharge development, with the majority dependent on PDIV, do not occur in a vacuum. As with treeing mechanisms, PD development generates from external stresses. In operating conditions, with significant time duration, insulation will experience stresses and operating voltages unaccustomed for by conventional testing, effectively facilitating the ageing process, referred to as thermometric ageing. With heightened operating stresses over time, thermometric ageing will be a large influence.

IEE IEEE Std 400™-2012 [1] list the following operating conditions as normal causes of cable ageing:

- Normal operating conditions.
- Location of application, e.g wet, dry etc.
- Overvoltages: Temporary overvoltages, switching overvoltages and steady state overvoltages.
- System configuration: Grounding set up, phase number, feeders etc.

It should be emphasised that each cable will experience unique operating conditions. If we combined this with the complexity of material composition for each given cable, predicting cable ageing for a given cable becomes a challenge.

4.3.3.1 Voltage rating influence on ageing

Due to the electrical stress applied to HV and EHV cables being significantly larger than the electrical stress applied to MV cables, HV and MVH installtions are more prone to changes in the local insulation breakdown strength, while MV installations are more prone to changes in the applied electrical stress. The typical stress experienced by different voltage rating is displayed in figure 4.9

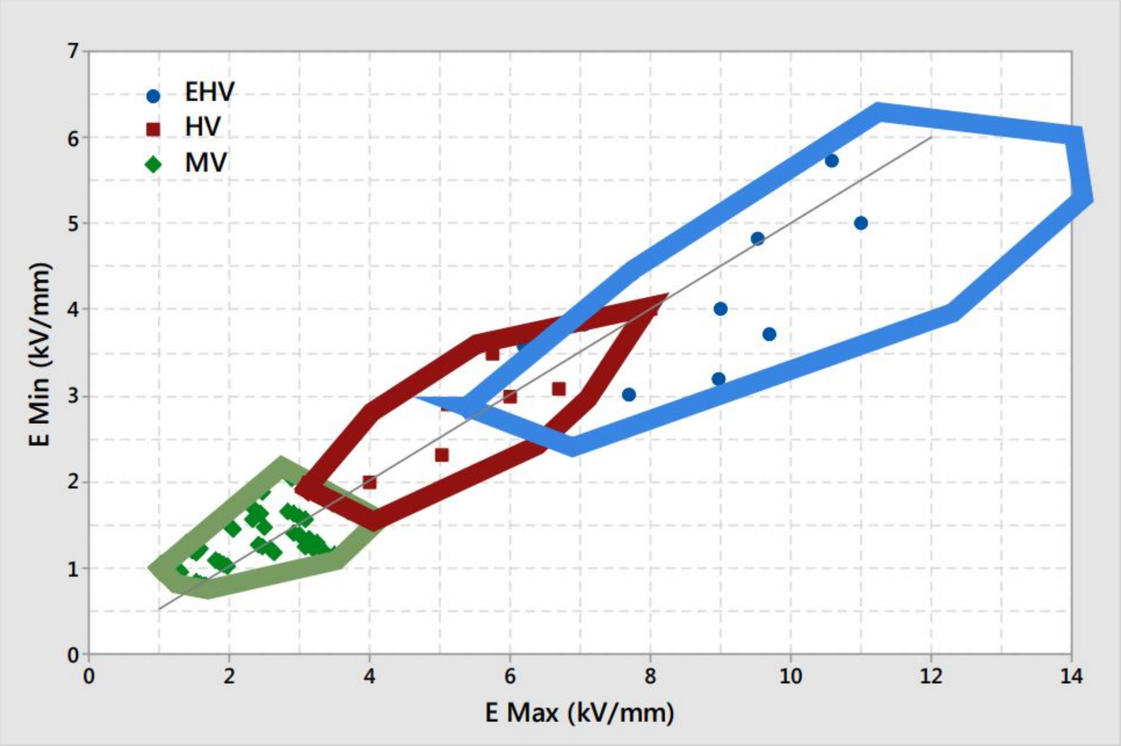


Figure 4.9: Typical electrical stress value for E, HV and EHV cables in North America, Neetrac DFGI 2016 [25]

4.3.4 Polarity Effect

The polarity phenomenon, or theory, articulates the electrical phenomenon of significantly amplified BDV in negative AC sinusoidal in non uniform fields. In AC induced conductors, waveform are sinusoidal, thus having positive and negative wave cycles. In negative stressed electrodes (negative cycle), the pre-discharge inception voltage is of relative low value, while BDV is relatively high. Positively stressed electrodes have relatively high pre-charge inception voltage, while BDV is relatively low, suggesting the probability of breakdown occurring in positive AC sinusoidal cycle [83] .

The phenomenon can be explained by the diverging characteristics between positive and negative electrode avalanche development. As previously discussed, positive electrode avalanche are comparably easier to initiate and achieve streamers, while negative electrodes experience delayed discharge delay and electron detachment. After accumulation of streamers, positive space charge generates at the head of the streamer, significantly reducing the electrical field in front of the electrode effectively resulting in lower localized BDV. The polarity effect is proven in both gas, liquid and solid state based insulation.

5 Cable history, statistics and development

5.1 Cable definition

This chapter aims to provide a brief overview of cable characteristics, historical progression, infrastructural shares and general cable fault statistics. Traditional paper based insulation will be briefly discussed, while polymer cable technology will be further discussed in depth.

Cables are widely defined as coaxial structured installations, with their own in built insulation, that conduct current with an earthed surface [24]. Traditionally the installment of cables have been paper based cables, while in modern installments polymer based installation are favoured. There is however reluctance to replace already installed HV paper insulated cables. In total it is estimated that cables make up for 15-20% of installed transmission capacity [20].

Voltage ratings of cable installation usually consist of medium voltage MV, high voltage HV, extra high voltage EHV, and even in more modern proposed installations, Ultra High voltage. In addition the power grid structure is divided into, given from highest order of transmission, transmission grid, regional grid and distribution grid. The terms and voltage ratings are however not internationally consistent. There will be discrepancies amongst countries in Europe, and even larger discrepancies across continents. For instance Norway operates with transmission grid, regional grid and distribution grid [41], while USA operate with transmission and distribution level. Norway define the transmission level from 132kV to 420kV, while America define it within the 66-138 kV range, and UK from 275-400kV. Thus discussing and operating within the theoretical field will pose challenging, unless keeping within the confines of a single country or a closed grid infrastructure. There will also be discrepancies between countries by equipment choice and standardization.

The terms describing cable types vary within the literature. Paper based cables can also be referred to as laminated dielectrics, and polymer cables are often referred to as extruded dielectrics. All cables share the same key construction, with conductor, insulation and various degrees of screens, shields, semicons, sheath and jackets. Modern cables are generally constructed so called fully armed, with sufficient layers protecting the conducting core. Due to advancements in cable technology the implementation of certain cable part postdates a large bulk of installed cables. Hence there are distinctions between jacketed, un-jacketed, shielded and non shielded cables. This is important to note when reviewing test literature as the purposes of the test, and its premises alter based on the construction of the cable.

A brief overview of typical modern extruded cable will follow. Figure 5.1 illustrates the cross section of typical modern jacketed power cable.

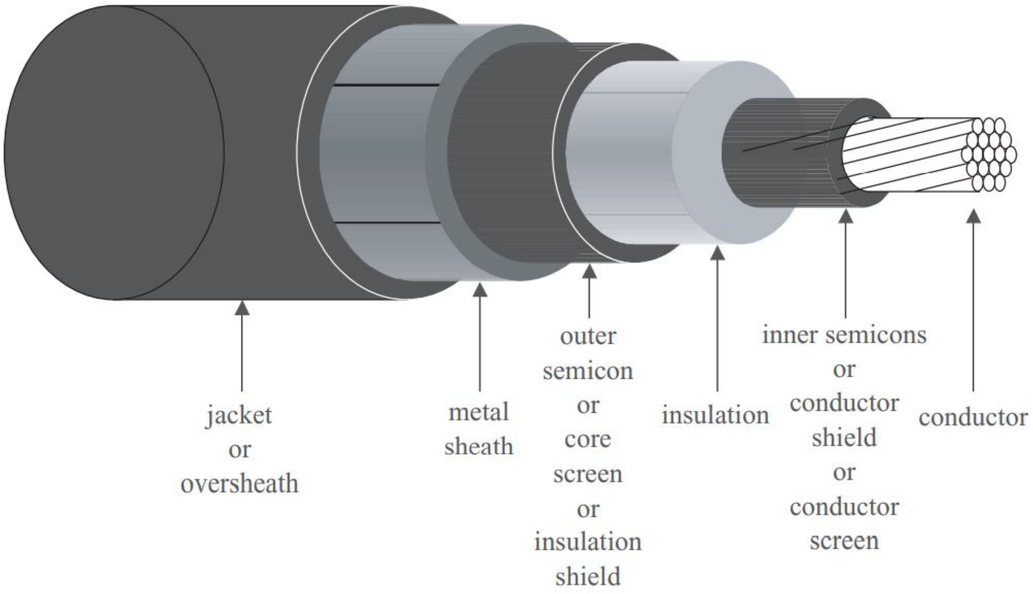


Figure 5.1: Cross section of a typical power cable [58]

A coaxial construction, power cables primarily consist of an inner current conducting core, insulation and an outer earthed conductor. As the interfaces between these layers are prone to voids and cavities, thus increased electrical stress, semicon layers are placed between aiming to smooth the transition between interfaces, equalize voltage stress and also the physical protection of the layers [11]. The two semicons are often referred to as conductor shield and insulation shield. Semicons consist of a polymer mixture utilizing the concept of carbon black, due to its excellent conductive properties [116] . The insulation shield is surrounded by a metal sheath. The metal shield serves as protection for the insulation by grounding potential surface voltages. The metallic shield is typically grounded to earth by multiple points across the cable system length. Externally comes the jacket, also known as the oversheath. The oversheath purpose is to protect the core construction form physical interference, external electrical interference and importantly water ingress.

5.2 Brief Cable History

The use of cables in power transmission has extensive history, being utilized already back in the 19th century. Traditionally the installed bulk of cables were fluid-impregnated paper based installations, while the last 50 years have seen a substantial transition to polymer based insulation, or rather extruded cables. The continuous incentive for changes within the industry can be summed by a desire to reduce size, failure rates, maintenance and installation costs, safety hazards, environmental hazards and perhaps most important reduce the dielectric losses associated with cables [102]. The paper based installation was widely considered as a matured technology at the end of its sovereign period. As the initial experimental use of extruded dielectrics yielded results far superior compared to standard laminated cables, a large shift towards to extruded cables in the 1950s and 1960s followed. The transition to extruded cables has however not been without issues. The detrimental effect of water treeing on the initial population of XLPE cables have already been discussed. The first generations of MV extruded cables were installed without jackets and appropriate protections in the inner layers, hence being prone to water treeing [58]. HV extruded cables have experienced significantly less water treeing after jackets and barriers were implemented. The transition have also encountered challenges in terms of size compatibility with existing infrastructure, as extruded cables vastly differs in size compared to it predecessors, complicating the replacement of old cables in ducts. The transition have however yielded improvements in the aforementioned performance criteria, and is considered a success [102].

The Neetrac Cable Diagnostic Focused Initiative (CDFI) of 2016 list the following milestones within the history of cable development [24]:

Year	Description
1812	First cables used to detonate a mine in Russia
1890	Ferranti develops the consentric construction of cables
1900	Cables insualted with rubber
1903	First screened cables
1917	PVC first used
1937	PE developed
1942	The first use of PE in cables
1963	Invention of XLPE
1967	Use of HMWPE insulation on underground cables in USA
1968	First use of XLPE insulated cables (mostly un-jacketed, tape shields)
1972	Failures due to water tree growth in polymer insulation revealed
1972	Introduction of extruded semiconducting conductor and insulation shields
1973	Super-clean XLPE insualtion used in HV subsea cables from Sweden to Finland at 84kV
1978	Widespread use of polymeric jackets in North America
1982	Water tree resistant (WTR) insulation introduced for MV cables made in Canada, Germany and USA
1989	Supersmooth conductor shields introduced for MV cables made in North America
1990	Widespread use of WTR-materials in Belgium, Canada, Germany, Switzerland and USA
1995	Use of water blocking in conductor strands (extruded mastic or swellable powders)
2000	Use of metallic shield and water swellable tapes around the extruded cores

Table 5.1: Cable Development Milestones [24].

Due to the constant evolution in cable technology there is no doubt that the currently installed cables have far superior performance than previous generations, both compared to laminated cables and the first generation of extruded cables. As a large bulk of present service cables stem from previous generations there is theoretically a finite amount of improvement present, if a complete overhaul was to be conducted. This is however not financially viable or financially possible with the current means. All installed cables have an estimated service time, typically ranging from 30-50 years. Although underground cables do no age uniformly, a general estimation of the service age of a population of cables is to be expected. Given the now relative long time since the large scale commercial introduction of extruded cables, the most flawed installations is either replaced or nearing their end of service time. After additional years the installed population of cables, will by mere replacement due to ended service life, enhance in performance and the population of installed extruded cables will in due time be regarded as a matured technology. This is however still relative far away, hence the dilemma should be how do we best utilize the current infrastructure.

Even in the foreseeable future when extruded cable technology reaches a mature status, the importance of operating conditions and it's influence on cable ageing can not be overstated. Thus, considering the apparent unattainable goal of reaching manufactural perfection, the focus on how to optimally utilize the equipment currently available is essential, rather than aiming for initial brilliance, since non-detected defects pre-deployment will statistically manifest themselves inevitably anyway.

5.3 Types of cables

Power cables are classified into four main types, based on their construction material [58].

- High pressure fluid filled HPOF
- Mass impregnated bin draining MIND
- Self contained fluid filled FF,LPOF
- Polymeric LDPE, HDPE, XLPE, EPR

5.3.1 Paper insulated cables

Also referred to as laminated dielectric cables. Traditionally the preferred cables of choice until the mid 1980s when polymer solutions got commercially viable. The different types of paper insulated cables all share generally the same structure and layers. The factor separating them is the use of fluid in the impregnated the paper insulation. In principal paper insulation is divided into two main types, self fluid and mass impregnated. Self fluid, SFFC, consist of low velocity impregnated fluid. Utilized in both HVDC and HVAC, but due to the requirement of refueling fluid, transmission exceeding 50km is deemed non viable[58].

Mass impregnated cables, MI, are impregnated with high velocity fluids. Unlike SFFC cables, MI has no distance restrictions, thus traditionally being the preferred choice in subsea HVDC. Recent development suggests MI cables will continue being a preferred choice, due excelent track reckord, level of knowledge and complexity of potential replacement.

In addition to polymer cables surpassing traditional cables in performance attributes, the continuing raised awareness of environmental effects in regards to fluid paper technology, creates a substantial incentive for a general out phasing of existing technology.

5.3.2 Polymer insulation

As a substitute for paper modification, polymer cables uses polyhtelyn, the most commonly used polymer (plastic). Polyethylene modifications offer exceptional insulation abilities at a relative affordable cost and uncomplicated design. Although the different polymer modifications vary to a degree in properties and quality, the general favourable properties can be summed as follows.

- Relative low electric stress
- High electrical treeing resistance
- Environmental value
- Design and maintenance

In polymer insulated cables, the four following types are of relevance: Crosslinked polyethelene (XLPE), ethylene propylene rubber(EPR), low density polyethele (LDPE) and high density polyethelene (HDPE). Of these four, XLPE and EPR have emerged as the commercially viable options to paper insulation, on account of their ability to operate at temperatures exceeding 90 C. LDPE is limitied to a operating temperature of 70 C, and HDPE 80 C [58].

5.3.2.1 XLPE

At present time, XLPE or Crosslinked Polyethylene, is the recommended high voltage cable in most voltage ratings, especially in medium voltage infrastructure. Given XLPE low dieletric losses, it can be applied in infrastrucure ranging up to 500 kV. By crosslinking the bonds in the polymers, XLPE aquires superior properties measured against PE insulation, such as Low-temperature impact strength, abrasion resistance and environmental stress cracking resistance. XLPE insulation is a thermoset, as opposed to thermoplastic, thus capable of withstanding high operating temperatures without altering structure.

The preferred method of crosslinking polyethylene in high voltage inuslation is the peroxide cure PE-Xa, while the moisture cure is seen as a viable economic alternative. Regarding degree of crosslinking, meaning extent of crosslinked bonds, PE-XA and PE-Xb have respectevility degrees of 75% and 65%, thus fulfilling the required amount of crosslinking set by ASTM Standard F876 [6].

Figure 5.2: Single core XLPE and three cored XLPE cable [76].

The substantially low dielectric loss of XLPE purposes as the main property in favour of XLPE cables, relative to EPR and paper alternatives, strengthening its dominance in long distance transmission. In a given scenario, a 132kV $1000mm2$ cable XLPE will operate with 5.1 mA/m, while a paper installation with similar parameters operate with 14.7 mA/m [58].

Currently the majority of new installments are XLPE cables [102]. Replacement of existing cables remains limited, due to convenience. Paper insulation still satisfies the vast number of system requirements, provides an excellent track record of life expectancy knowledge and lastly the project of replacing functioning installments will in certain situations be deemed unenviable both economically and environmentally. Replacements have as well historically proved challenging, due to the sheer size difference of XLPE compared to paper installations. Since continuation of using existing pipes and conducts is essential, fitting XLPE cables, which historically have been about 40% thicker than paper have required alternative solution of XLPE cable designs in replacement operations in order to be flexible enough [58].

Initially the major drawback of XLPE, as with the majority of newly introduced technology, was limited track knowledge. Despite superior insulating properties, simpler design and lower maintenance, limited ageing tests, fault statistics and compatibility knowledge, makes transitional overhauls in the transmission infrastructure risky investments. By now, XLPE cables have experienced over 30 years of commercial usage, and enjoy extensive track knowledge, which pays relevance in terms of cable fault monitoring, to be discussed in subsequent chapters.

5.4 AC and DC

S. Le Blond, R. Bertho, D. Coury, and J. Vieira, “Design of protection schemes for multi-terminal hvdc systems,” Renewable and Sustainable Energy Reviews, vol. 56, pp. 965–974, 2016. [2] K. Sharifabadi, L. Harnefors, H.-P. Nee, S. Norrga, and R. Teodorescu, Design, Control and Application of Modular Multilevel Converters for HVDC Transmission Systems. Newark: Wiley, 2016 bruk disse som kilder for å anbefale DC

Outwardly AC cables and DC cables share a lot of similarities both in function and material structure. They do however differ in key properties, material and engineering related to the cables system. In power transmission AC cables are the preferred alternative and accounts for approximately 98 % of the installed global cable population [58]. This is due to the relative small losses at low distance transmission, the ability of regulating AC systems, low cost and simplicity of maintaining and operating the system. Seeing AC technology win the ”The Current War” against DC, AC have experienced a rich history of progression and inventions since its infancy.

DC have more limited history and did not get utilized in power transmission until 1954 when Gotland was connected to mainland Sweden by cable[86]. Given the average length of a typical cable distance being within the functional threshold of AC properties, AC cables are and will be the suitable alternative for the majority of cable distances. The performance of AC cables have a significant drop of at longer distances, due to large capacity currents. A DC cable conducts current uniformly across the cross-section of the conductor, this not being the case for AC where the flow is non uniform and the current flows near the surface, or rather the skin, of the conductor. This is known as the skin effect. An AC applied voltage induces a magnetic field in and around the conductor. The magnetic field is alternating whenever there is change in current intensity. This results in the magnetic field directly opposing the change in current, this is known as back electro magnetic force

(Back EMF). Eddy currents are generated which forces the current distribution to migrate towards the conductor surface. The extent of skin effect enlarges with the increase of frequency. More on skin effect can be read at [136].

The skin effect results in significant high resistance in AC cables compared to its counterpart DC, thus experience larger power loss in transmission. Due to the requirement of several conductors to support the multiple phases of an AC cable, there will be significantly higher capacitance in AC cables compared to DC. An increased amount of current is required to energize, or rather compensate for the high cable capacitance, resulting in increased power loss. Both the capacitance and reactive losses increase with AC cable length. It should be noted that since DC constructions are not required to support multiple phases, coupled with ability to operate with thinner conductors due to absence of skin effect, DC cables have substantially higher capacitance than AC cables. By construction design underground cables have higher capacitance than overheadlines, and again subsea cables have even higher levels of capacitance. A more detailed discussion of the electrical performance factors of AC vs DC cables can be read in the paper by T.Halder [59].

Usually when comparing the benefits of AC vs DC installations, the cost and efficiency of the system are essential. In which situations does a DC solution manifest itself as a superior alternative? This typically boils down to a matter of cable segment distance, both for underground cables and overheadlines. Despite the aforementioned superior transmission abilities of DC, there are some major drawbacks limiting the utilization at short distance transmission. The drawbacks can be divided into three categories: Costs, difficulty with voltage control and complexity, e.g system engineering and system compatibility with existing grid. The initial cost of implementing a DC cable system is high for DC systems. This is due to the expensive equipment linked to power conversion and switching, as they both tasked to regulate DC voltage level while simultaneously converting from DC to AC and vice versa. The lines or cables themselves are not more expensive, on the contrary they are often cheaper due to less construction volume required to transmit power. The decrease in volume is due to less conductors phases required to transmit power. A direct result of this is the decreased space occupation DC demands, known as right of way (ROM). The decrease in right of way will be beneficiary as it simplifies the bureaucracy associated with getting land owner permission. The installation price is then compared to the projected operating cost. The operating cost accounts for cost related to operating the line and maintenance. Due to the large power losses experience over long distance AC transmission, the cost of operating an AC line will inevitably exceed the initial high cost of a DC line. The cut away where operating costs catch the installation costs, is known as the break even point, or rather break even distance as it's so distance dependent. The concept of break even distance is illustrated in figure 5.3.

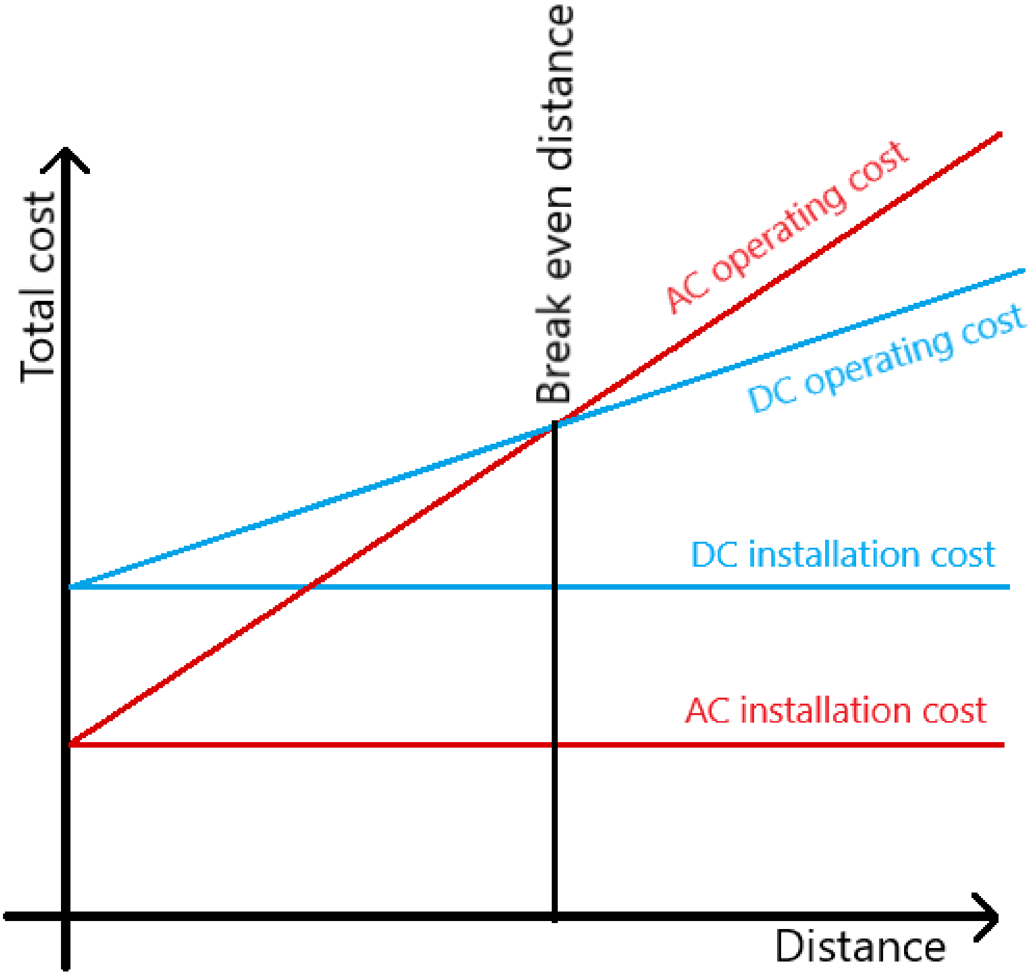


Figure 5.3: Break even distance of AC and DC [59]

This is one of the key parameter for determining between DC and AC. The break even distance is not a definite value, and will vary based on the total cable system inferring the given cable length, due to the various costs related to operating a system. There are however general guidelines based on merit. The total capacitance of the cable system usually indicates the break even distance. For an overhead line the breakaway distance is estimated in the 600-800 km range, underground cables in the 50-100 km range and finally subsea cables 20-50 km range [58] [59]. This is a great reflection on traditional transmission, where the utilization of DC has been mainly limited to underground cables and been a speciality for subsea installations. In the case of subsea cables and certain underground cables, the critical function they serve in tranmission system warrants the initial costs and complexity of the system. In the case for overheadlines the potential of power loss have not exceeded the other problems related to DC implementation. There is however an increased industry interest in HVDC overheadlines as transmission, partly due to shift towards renewables, but also because of large improvements greatly reducing the cost and complexity of a HVDC system, creating larger incentives for choosing HVDC.

Two of the largest issues limiting the utilization of HVDC have been the cost and complexity of voltage converters and the poor performance associated with circuit breakers. DC circuit breakers have traditionally struggled with meeting the speed requirements associated with acceptable fault protection, which is problematic both for the power converting equipment but also for the stability of connected AC grid [94][10]. The three main categories of DC CB are mechanical CB, Solid State CB and Hybrid CB. Recent studies indicate the utilization of hybrid CB as sufficient CB for hybrid DC/AC grids. The drawbacks of mechanical CB are slow fault interruption time, while solid state CB struggles with high power loss (30%). Hybrid CB improves upon these characteristics and offers fast operating speed and low power losses. The major drawback related to hybrid CB is high costs and the fact the technology is still in its infancy, as there are no clear cut commercial alternatives available currently. Due to advancement in the recent decades the ongoing large scale introduction of HVDC grid should be a surmountable task.

The current evolution of our energy system poses new challenges for our infrastructure. There will be an increased demand on electricity as there is a transition away from fossil fuels, requiring increased capacity both at transmission and distribution level. The renewable energy sources are typically generated far from the vast bulk of consumption and has to be transmitted long distance. There will be larger emphasis on interconnected transmission between countries, either by the means of intercontinental-scaled grid, or transmission highways, subsea connections and underground cables. The integration of renewable energy sources also introduces a new dynamic in power flow as most renewable sources can be regarded as DC [87]. To elaborate on this: The introduction of especially solar and small scale wind are DC sources. In addition the proposed battery solution linked to non-regulated renewables are also DC. A large quantity of load consumption are DC based, e.g cellphones, computers and etc. These have all been established ”loads”, recently there has however been a large alteration in load consumption with the large scale introduction of electrical vehicles, predominantly cars and various urban vehicles, but there are also long term plans on commercially integrating both maritime and aviation alternatives [132][7]. Normally this energy would be transmitted via a double conversion, e.g DC to AC and lastly AC to DC conversion. Ideally there would be no conversion between generation and load, thus reducing power loss and overall cost. If we combine this with the remote location of a majority of renewable energy generation, HVDC out-crystallizes as a glaring solution.

Typical scenarios can be found in the UK where wind generation is either based offshore, such as the Hornsea 1 wind park or in wind farms in remote land areas far from the metropoles, Japans plan to connect to continental Asia in order not to depend on self sustained generation, the brand new Northconnect cable connecting Norway and Scotland, which effectively becomes the world longest subsea cable or the mass inland hydro power generation supplying a population dense coast of China.

Apropos, China have been forerunners in regards to implementing HVDC systems and can be consider to operate within the state of the art within the technology. Due to the majority of power generation either being situated in the west with hydropower and the northwest with coal and the load consumption situated along the coast, combined with an unprecedented growth in power demand due to massive economic growth, the HVDC appears as the logical option. In terms of voltage rating we are now referring to ultra high voltage (UHV). China both operate with UHVAC (1000 kV),UHVDC (800 kV) and UHVDC (1100 kV), and where the first in the world to utilize a UHVDC link in the Yunnan - Guangdong link [66] (2010) and the world largest UHV link Zhundong–Wannan 1100 kV link completed in 2019 [123]. In total China has completed 28 out of 35 proposed UHV, already forming UHV grid connecting the six different regions of China and is planning on additional grid connecting the rest of continental Asia [106]. It should be emphasized that China is way ahead of the curve and no other country have indulged into UHV transmission to the same extent as China. The project has however not been risk free, encountering issues with AC/DC converting, stability issues in the existing grid due to UHVDC consuming reactive power, as well a general vulnerability due to insufficient protection and back up systems in place [89][128]. Unexpected blackout of central UHV lines would cause major repercussion in the surrounding grid, effectively causing major power blackouts.

Despite global hesitancy to the Chinese accelerated approach toward UHV grids, it’s a window into the future of global transmission, albeit not necessarily with the same approach as China. China has already proposed plans for a global UHV grid serving as a backbone in a global power flow by 2050 [55]. Europe has already developed a sturdy continental grid and is increasing the connection with the British Isles and Scandinavia by interconnected subsea cables (Northconnect, Circle South etc)[100]. These efforts are coordinated by the European Union Agency for the Cooperation of Energy Regulators, commonly known as ACER. The U.S are trailing behind and are experiencing an outdated fractionalized grid consisting of three separate grid systems. The issues became apparent in the aftermath of the Texas Power Outage due to a winter storm in 2021 [99]. The proposed global UHV grid from China has met skepticism. As China is the leading force on large scale deployment and associated innovating technology, they effectively gain a large quantity of the market share within an essential field. By proposing international standards on UHV technology China aims to be the leading force in global energy. China has already obtained 9 IEEE accepted standards on UHV [74]. More on China's advancements toward global standardization can be read in the report issued in 2015 by the Argonne National Laboratory [104].

Due to the limited utilization of HVDC systems, HVDC have historically been regarded as a specialized field and have thus been allocated far less attention than AC technology. Hence there has been limited research into the various potential of utilizing HVDC, but additionally limited studying on the nature and monitoring of DC systems. The limited knowledge on HVDC monitoring does not harmonize with the current mass introduction HVDC grid and will be a large priority for the industry going forward. There will both be advocated a lot of research into fault protection and fault monitoring. An essential part of developing adequate DC monitoring techniques is to enhance the current knowledge on DC cable ageing, as the the ageing properties differ from the more in depth explored AC cables. Monitoring of DC systems is discussed in chapter 6.9.

5.4.1 DC ageing properties

The main measurable parameter differentiating AC and DC monitoring is the absence of a phase angle in DC as it conducts without any frequency [62]. Allthough not deeply researched, studies have indicated that PDIV in DC is significantly higher than AC, but is sensitive to temperature fluctuations [120]. At room temperature the PDIV in DC is significantly lower, but at max operating temperature, e.g max load, the PDIV may exceed AC PDIV values. The study indicates that for a given XLPE cable, the DC PDIV will exceed the AC PDIV at cavity fault temperature of 65 degrees. This indicates that sufficient knowledge on DC operating temperature is essential to develop appropriate monitoring and prevention techniques.

5.5 Tests

Several tests, predominantly mandatory, are conducted both prior and after installation in order too satisfy manufacturers and industry standards [58]. These test, as in the case of XLPE cables, account for a wide range of insulation property characteristics, simulating an operational life cycle of the said cable. The test will however only be simulations, and will not accurately account for the realms of operating conditions stressing insulation, such as the occurrence of water treeing in the first generation of XLPE cables. Due to large discrepancies in cable quality, ageing test will result in vastly different test results, hampering the statistical foundation which predictions are based on. Only the progression of time, regularity of testing, increase in cable knowledge and continually improving testing methods and routines will improve the quality and standard of commercial installations.

In broad terms cable testing can be divided into to main categories. Pre-deployment tests and post-deployment tests. Pre-deployment tests address the quality of a manufactured cable and check whether or not the cable is in accordance with dimensional, material and electrical requirements. May also be referred to as factory tests. Post-deployment tests, also referred to as maintenance tests are conducted on aged cables, or rather in service cables, to assess the current condition of the cable system. This sub-chapter will assess pre-deployment tests, while post-deployment tests, or rather maintenance tests, will be assessed in chapter 6.6.

Polymer cable testing pre-deployment can be classified in the following groups:

- Installation tests
- Acceptance tests
- Prequalification tests
- Type tests
- Sample tests
- Routine tests

Test categorizations are interchangeable with different utilizations of the terms being used within the field. The terms have also evolved through time, especially since the requirements and standards have improved. The following categories are utilized by IEEE, and is explained in detail by Haddad [58].

Installation Test

Test conducted prior to system connection in order to detect potential installation, shipping and storage damage to verify whether or not the cable parameters match the pre deployed measurements. Installation tests are not specific in each case, and depends solely on the test conductors requirements. After implementing the cable in the system, these test are replaced by acceptance tests and maintenance tests.

Acceptance tests

Test conducted prior to to service deployment. Cable needs to pass the acceptance test prior to service. This will also be the case for repaired cables getting reinstated into to the cable system. The tests have to be repeated until passing before service deployment.

Pre-qualification test

Pre-qualification test are only included for testing MV and EHV and not for HV. The tests are carried out in order to satisfy the manufacturers before further mandatory tests are applied, in essence testing if their products function at the intended use. The conducted tests are primarily tests to simulate operating conditions, in order to test how the cables cope with the wide range of interior and external stresses expected in typical operating circumstances. Pre-qualification tests are both extensive in scope and duration, often lasting 1-2 years.

Type tests
Type test, as the name implies, are test conducted in order to qualify a particular design of cable, thus only required to be conducted once. Type tests include partial discharge testing, a variety of stressing tests and mechanical property tests.

Sample Testing
Test conducted in order to check if the cable fulfills its specified values and limits. Tests are carried out on a randomly picked reel of the manufactured cable. Values such as capacitance, electrical resistance as well as dimensional parameters such as density are controlled.

Routine Testing
Concluding part of the testing phase. All manufactured cables must undergo PD and voltage withstand test before dispatching. Test values correlate to typical operating conditions. More on withstand test can be read in chapter 6.6.4.

5.6 Fault costs

Experiencing faults within the power grid may result in circumstantial costs, be it due to power loss, material costs, repairment and etc. Deploying monitoring and diagnostic techniques is on the hand also expensive. The balance between fault costs and monitoring/diagnostic costs is at the focal point of power policy. Should the power sector have a proactive or reactive approach to failures in the transmission grid?

Within the field the term run to failure (RTF) is used to describe whenever equipment goes untested through its service life time, a reactive approach to cable maintenance. Run to failure strategy can be defined as: ”When assets are deliberately allowed to operate until they break down, at which point reactive maintenance is performed” [46]. There will always be a certain degree of RTF within the HV cable sector, as the large population of cables may go unaccounted for and failure may occur sudden against statistical probability. In the CDFI of 2014 Neetrac revealed that 56 to 74% of cables where RTF [23]. Meaning that only approximately a third of all installed cables underwent diagnostic measures during service time. Neetrac also states that the usage of diagnostics have increased since they conducted similar studies in 2006. This indicates a shift in approach.

The total cost related to cable faults can be categorised into four: Installation costs, cable system operational life costs, reliability upgrade costs and end of life costs [23]. As the focus of this paper is the monitoring of high voltage equipment, the second category, cable system operational life costs, will be further discussed. The costs can further be divided into:

- Maintenance
- Cost of fault/outage
- Diagnostics
- Service Restoration
- Repair and replacement

The total cost related to maintenance of a given cable system understandably varies and is depended on various aspects. Still the majority of categories listed above have rough cost estimations. Materials and tools needed for repair have tangible costs, as well does the work related to diagnostics and repairment as they usually are calculated on a per day basis or per unit basis. The large uncertainty in cost estimation is cost related to system downtime. The cost estimation post outages can be uncertain at best, and cost estimations pre-outage can only be based on expected statistical downtime. Complicating the procedure of cost estimation is the fact that not only will the power loss cost be taken into account but additionally the societal cost of grid costumers. These are complex calculations as they need to account for the number of customers, their median income and etc. Although near impossible to accurately calculate, rough estimates may be obtained. In the U.S, The Department of Energy have provided a calculator tool named ”Interruption Cost Estimates” (ICE) [43], which aims to estimate the total costs related to outages due to grid failure. Despite being a helpful tool, ICE have limited applicability as it’s unable to calculate major outages with substantial downtime [23].

A key dynamic in the overall cost picture of a cable system is the potential harmful nature of monitoring and diagnostic techniques. The harm may accelerate the ageing process of a cable or in some cases lead to breakdown, which in certain situations may be a desirable outcome.

In the estimations conducted in the Cable Diagnostic Focus Initiative (CDFI), it was concluded that if the cost related to power outages were to be ignored, there would be situations where it would be deemed financially reasonable to operate with a proactive approach. A reactive approach, also known as run to failure, may be the right choice in certain cases. However as the cost of outages are undeniably an important factor, the overall cost assessment is in favour of a proactive approach [23].

5.7 Fault Statistics

Failure and breakdown in cable transmission have extensive repercussions in the power grid. Locating and repairing underground cable faults are a costly procedure, with repair duration typically spanning up to a weeks time. If by chance, the fault occurs in sub-sea cable installations, costs and duration are expected to substantially increase, often taking months to repair. More crucially, the sudden lack of transmission in the now non operating cable may prove critical in the grander scheme of the transmission system.

Faults in cable systems can be divided into three categories: Third party damage, faults in accessories and fault due to cable insulation. Third party damage consist of external influences physically interfering with the cable system, causing failure and malfunction, ranging from weather induced interference such as erosion and earthquakes, to man made interference such as construction work and ship anchors. Despite the large emphasis put on the importance of ensuring cable insulation health in regards to cable reliability, both in this paper and other field literature, faults due to insulation breakdown only make up a small percentage of the total cable system faults. In fact faults due to third party damage and accessories make up a large majority of the faults.

A french study conducting in 1999 [17] studying MV cables in France, provides statistics for cable faults. The failure is given in failure per 100 km cable per year for MV XLPE cables. The results are show in table 5.2.

Failure Type	Fault rate (number/year/100km)
Total System Faults	2.0
Third Party Damage	1.0
Accessories	0.9
Cable	0.1

Table 5.2: Failure rates XLPE cables in France 1999 [17]

The study discovered a strikingly low prevalence of insulation induced cable faults. Additionally when the study compared the failure rate of XLPE with the failure rates of laminated cables, while excluding third party damage, XLPE cables were 2.5 times more reliable than laminated cables.

These results harmonize with result found in the CDGFI of 2016 [24] shown if figure 5.4.

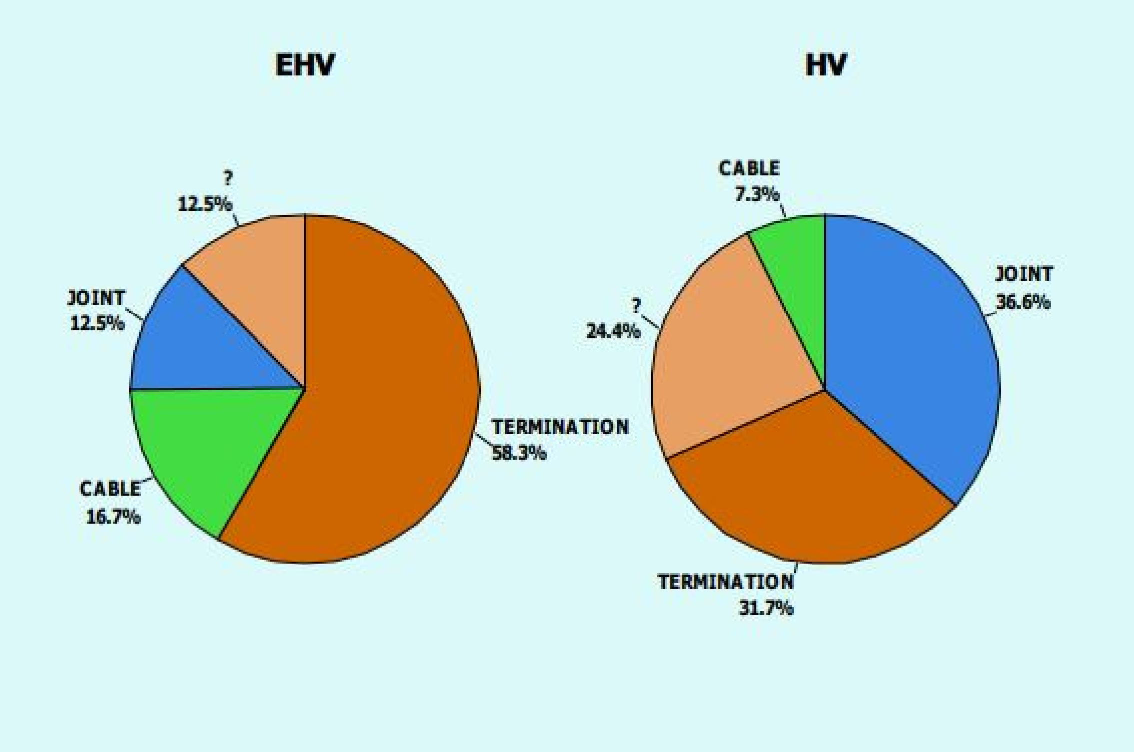
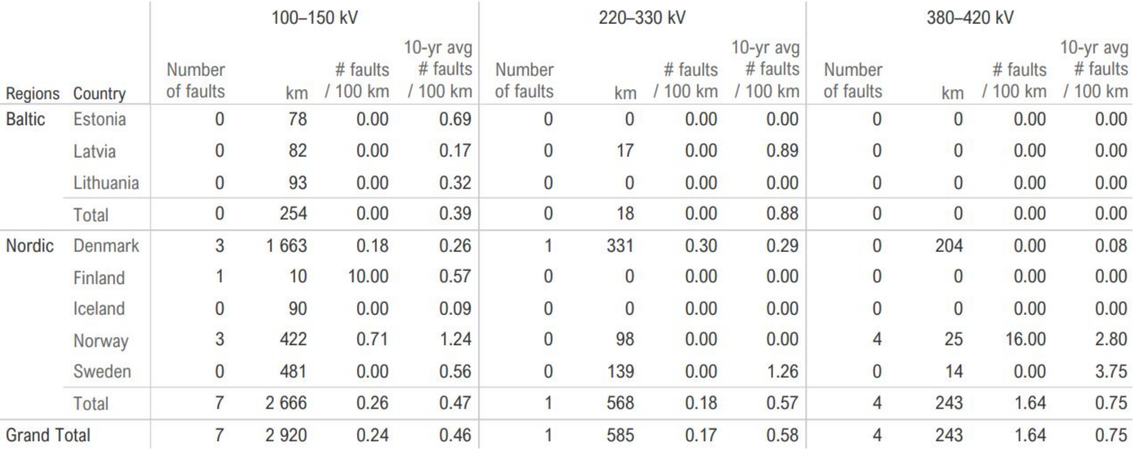


Figure 5.4: Origin of cable faults for HV and EHV cables in North America in the period 2000-2016 [24]

The pie charts illustrate the origin of cable fault in North America extracted from the period of 2000-2016. The results also show that only a small percentage of cable faults can be contributed to the cable itself, but rather at the accessories of the cable.

ENTSO-E which provides annual report on transmission faults, also operate with faults per year per 100 km length. In their 2019 report [101] they provide average annual fault for the 10 yer period of 2010-2019 for the Nordic and Baltic countries, shown in figure 5.5.



		100–150 kV				220–330 kV				380–420 kV			
Regions	Country	Number of faults	km	# faults / 100 km	10-yr avg # faults / 100 km	Number of faults	km	# faults / 100 km	10-yr avg # faults / 100 km	Number of faults	km	# faults / 100 km	10-yr avg # faults / 100 km
Baltic	Estonia	0	78	0.00	0.69	0	0	0.00	0.00	0	0	0.00	0.00
	Latvia	0	82	0.00	0.17	0	17	0.00	0.89	0	0	0.00	0.00
	Lithuania	0	93	0.00	0.32	0	0	0.00	0.00	0	0	0.00	0.00
	Total	0	254	0.00	0.39	0	18	0.00	0.88	0	0	0.00	0.00
Nordic	Denmark	3	1 663	0.18	0.26	1	331	0.30	0.29	0	204	0.00	0.08
	Finland	1	10	10.00	0.57	0	0	0.00	0.00	0	0	0.00	0.00
	Iceland	0	90	0.00	0.09	0	0	0.00	0.00	0	0	0.00	0.00
	Norway	3	422	0.71	1.24	0	98	0.00	0.00	4	25	16.00	2.80
	Sweden	0	481	0.00	0.56	0	139	0.00	1.26	0	14	0.00	3.75
	Total	7	2 666	0.26	0.47	1	568	0.18	0.57	4	243	1.64	0.75
Grand Total		7	2 920	0.24	0.46	1	585	0.17	0.58	4	243	1.64	0.75

Figure 5.5: Fault rates for cables in 100-150 kV, 220-330 kV and 380-420 kV range in the Nordic and Baltics in the period 2010-2019 [101]

The annual fault rate is significantly lower than from the results in France, which may indicate an overall improvement in cable system reliability. Whether this can be contributed to third party damage, accessories or cable insulation is hard to tell. Due to the relatively low sample size the cable population in the given countries represented, it can not be made any definite comparisons. What is interesting however, is when directly comparing the annual fault rate for cables with the annual fault rates for OHLs in the same sample region an interesting pictures evolves. When comparing cables against OHLs in the 100-150 kV range, which inhibits the largest amount of installed km, 2920 km and 59 066 km respectively, a clear trend can be seen. The annual fault rate for a cable is 0.46 # faults/ 100 km compared to 1.70 # faults/ 100 km for OHLs, e.g 3.7 times higher fault rate. This indicates an overall higher reliability of cables compared to OHLs.

To summarize, the majority of faults in cables can be contributed to third party damage and accessories, while faults stemming from the cable itself only contribute to a minor extent of the total number faults. Prevention and protection against third party damage is a complex and unpredictable operation, and will not be covered in this paper. The prevention against accessory and cable faults will be discussed subsequently in chapter 6.6.

6 High Voltage Monitoring

6.1 Benefits and purpose of high voltage monitoring

This chapter aims to cover the extensive field of high voltage monitoring, in which high voltage cable monitoring remains the main topic. As the paper intends to shed light on the current state and future outline of cable monitoring, it also discusses established technology. The historical development of monitoring will be discussed first, with subsequent current and future technology following. Techniques and methods discussed in subsequent chapters will be applicable for monitoring of the majority of high voltage equipment, including transformers, motors, circuit breakers and other accessories. Although eminently important to the operating conditions of high voltage cables, these accessories are not the focus point of this paper. There will however be provided a brief overview of methods used in the respective equipment, seeing that the monitoring techniques have much in common.

The reader should be reminded of the constant evolution within the technical development of high voltage diagnostics. Techniques discussed in the subsequent chapters are under constant review, both new and aged, and there is no firm guarantee for the continued use, especially for the newly proposed developments. Techniques which displays promise, may at the current stage have major flaws effectively prohibiting commercial use and the requirement of standardization. Solutions to these flaws may likely be found, but here are no guarantees. Also it should be emphasised that there is no ”true” approach to cable diagnostics and no methods should be pre-selected at merit, as the complex nature of cables systems should rather compel the user to chose suitable techniques for each given situation.

While traversing the field of high voltage monitoring the user will encounter discrepancies in regards to the utilization of standards. By obtaining industry standards the effectiveness of a given method will increase. Certain methods have however not progressed to this state, due to either major flaws, inability to quantify measures or the complexity of techniques applied. For instance, there are no industry standards for interpreting PD measurements [20].

Lastly it should be noted that the interpretations of the obtain measurements discussed in this paper are not deterministic, but rather probabilistic as the results at hand may only indicate outcomes and not determinedly predict an outcome. Most standardized methods should provide recommendations for further actions. Typically this will provided in the form of no action required, further study advised and action required.

6.1.1 Type of measurement

High voltage testing is divided between destructive and non-destructive tests, and between online and offline tests. The use of the terms invasive and non-invasive testing, is also central in the field literature. Ideally all test would be online non-destructive test, e.g no system downtime and no harm inflicted on plant items. There are numerous types of these tests, however the test result they yield are seldom satisfactory, especially in large, more complex installations. An example of an online non-destructive test is the use of thermography on busbars, OHLs and insulators. In terms of cable monitoring thermography displays its limitations, as it’s rendered near useless while applied on buried systems and is also unable to detect certain defects in accessible cables. Non-destructive test are usually conducted on non enclosed systems, as the nature of enclosed systems, such as transformers and cables prevents sufficient detection of the measuring devices.

High voltage insulation test, especially conducted on cables, simulate operating conditions by stressing the cable by applying voltage. These tests are conducted generally with two main objectives: Discovering the location, number, and magnitude of faults and voltage withstand testing. A natural consequence of these tests is the ageing stress applied on the test object. Significant damage can be inflicted on cable installations with certain types of test, which in itself may lead to breakdown. If preliminary testing reveals substantial deterioration, stressing the cable to breakdown with subsequent repairing is often a preferred course of action.

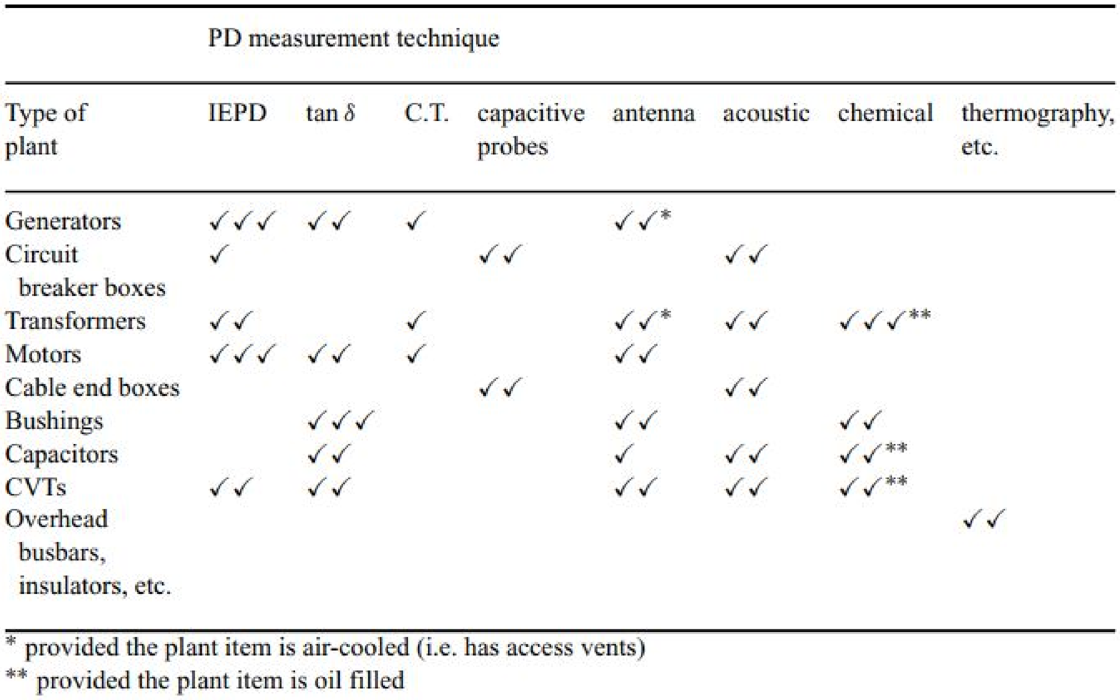
The difference between online and offline testing is not as large as the discrepancies between destructive and non-destructive testing. In a large part of testing, both online and offline testing are viable solutions, with methods providing both options. Offline tests are tests where the main power source is disconnected and an alternative voltage source is connected. Offline testing is often preferred due to the extended ability to regulate applied voltage and the obvious advantages of being in a test environment. Online tests are conducted with normal operating service voltage, typically 50 or 60Hz. The advantages of online testing is the reduced work related to preparing the setup, and the omission of the potential cost of outage of the connected power system due to down time related to offline. These types of tests also enable the possibility of temporary and permanent monitoring [1]

Although a scenario of an extensive field of non-destructive online measurement might seem far fetched, and unattainable in certain sections, continual improvements are being made. Since the potential benefits are so radical for the effectiveness of the power sector, current and future interest of enhancing these aspects of monitoring will be significant. For an in depth information on non-destructive test consult in the World Conference on Non-Destructive Testing [135]. What will reveal itself is that most of the techniques subsequently described will share a great deal of similarities in the way they are set up. the factor often differentiating the methods will be voltage source applied, as the voltage type and belonging characteristics can significantly alter the premises of the measurements.

6.1.2 Accessories

As previously mentioned, a large of cable failure can be linked to faults within accessory equipment. Since most accessory equipment can be located in plant stations, the time required to locate faults is substantially lower than the localization for cables, although repair time vary between equipment. The main factor differentiating monitoring of accessories with cable monitoring is the aspect of distance. It’s imperative to approximately localize PD breakdown in cables in order to conduct repairs, unlike with other accessories where localization may only be a minor issue. Thus, the techniques of cable monitoring have evolved into a special field, differentiating it from other methods, although the principles still remain the same.

As several monitoring methods are applicable to each plant equipment, the decision will be based first and furthermost on monitoring related costs balanced against the probability and potential consequence of failure. Another dimension worth considering is the information that can be extracted from each method, in terms of improved knowledge, enhanced statistics and life expectancy models. Figure 6.1, gives an overview of the monitoring techniques which are viable for the different types of plant items [58].



	PD measurement technique							
Type of plant	IEPD	tan δ	C.T.	capacitive probes	antenna	acoustic	chemical	thermography, etc.
Generators	✓✓✓	✓✓	✓		✓✓*			
Circuit breaker boxes	✓			✓✓		✓✓		
Transformers	✓✓		✓		✓✓*	✓✓	✓✓✓**	
Motors	✓✓✓	✓✓	✓		✓✓			
Cable end boxes				✓✓		✓✓		
Bushings		✓✓✓			✓✓		✓✓	
Capacitors		✓✓			✓	✓✓	✓✓**	
CVTs	✓✓	✓✓			✓✓	✓✓	✓✓**	
Overhead busbars, insulators, etc.								✓✓

* provided the plant item is air-cooled (i.e. has access vents)
** provided the plant item is oil filled

Figure 6.1: Method applicability for conventional methods utilized on typical plant items [58]

This paper will mainly focus on the monitoring of SF6 systems and extruded cables. However a brief overview of the monitoring of relevant plant items would be beneficial as the techniques and principles are relevant for cable monitoring. By structuring the chapter in this manner, it is aimed to shed light on the subtle differences between cable monitoring and other plant item monitoring.

The following methods of PD detection will be briefly discussed:

- Eletrical Monitoring
- Chemical Monitoring
- Acoustic Monitoring
- Thermographic Monitoring

6.2 Electrical Monitoring

The largest and most diverse branch of PD detection, electrical detection is based on the measurement of electrical units affected by PD activity. The field of electrical detection distinguishes itself from its respective counterparts in the amount of depth of detail and precision, granted success, it offers the user. It is also the most versatile detection field, having methods applicable for the majority of plant items. Traditionally there are three main approaches in order to detect PD activity:

- Individual discharge pulse measurement
- Electrical losses measurement
- Electromagnetic field measurement

6.2.1 Individual discharge pulse measurement

The main challenge of individual discharge pulse measurement is to establish isolation of the measurement object. To validate a detailed results, one would have to ensure all signals are from the item of interest and not interference from elsewhere in the power system. The general setup of discharge measurement consists of current measuring circuits with output connected to an oscilloscope. The cheapest and most elementary method is to utilize a clampon current transformer linked to an oscilloscope. The CT is connected to the measurable item at the neutral terminals. In addition to being a cheap alternative, the CT method can be conducted while the system is in operation, thus being a low treshold measuring technique. This is essential, because of the high importance of high intensity PD measuring regularity in order to monitor degradation development. A similar setup can be obtained by the use of the Rogowski coil [115].

The coil utilizes the concept of electromagnetic flux. The coil is coupled around the current conducting measure object. The current flowing through the conductor creates an alternating magnetic field in the coil, inducing voltage. The voltage induced is proportional to the current conducted, thus changes in the voltage may imply current discharges in the measure object. The Rogowski coil has grown increasingly popular, and its rise to prominence can be attributed to its versatility, flexibility and ability to determine pulse direction.

$$v(t) = \frac{-AN\mu O}{l} \cdot \frac{dl(t)}{dt}$$

Where $\frac{dI(t)}{dt}$ is the derivate current change in the conductor.To proportionals the output voltage to the conducter current, the voltage induced is integrated.

$$Vout = \int vdt = \frac{-AN\mu 0}{l} \cdot I(t) + Cintegration$$

The signal output received, usually in a oscilloscope, consists of the following: The amplitude of each discharge signal, the population of discharges per cycle and their phase angle. These three parameters make up the φ–q–n plot, which will soon be discussed. Simplified, the discharge amplitude indicates the the severity and size of discharge sites, the number of discharges per cycle indicates the amount of discharge sites and the phase angle indicates the location of the discharges. Additionally the location of discharges on power cycle indicates the type and environment of a given discharge.

For instance, if discharge signals occur symmetrically on either side of the voltage peak, it would indicate the site located besides or contained in a metal surface [58]. After surveying the nature, amplitude and number of discharges sufficiently, offline voltage ramp tests usually follow. Voltage ramp test are conducted in order to gauge the inception voltage of the different discharges. In summary, the amount of information gathered by relative simple measurement setups is quite significant.

As previously mentioned the information gathered by discharge signals can be combined into a useful plotting tool known as the φ–q–n plot. Granted sufficient data basis and adequate computer capacity, φ–q–n plot can serve as a modelling device for the given plant item. Figure 6.2 displays a φ–q–n plot.

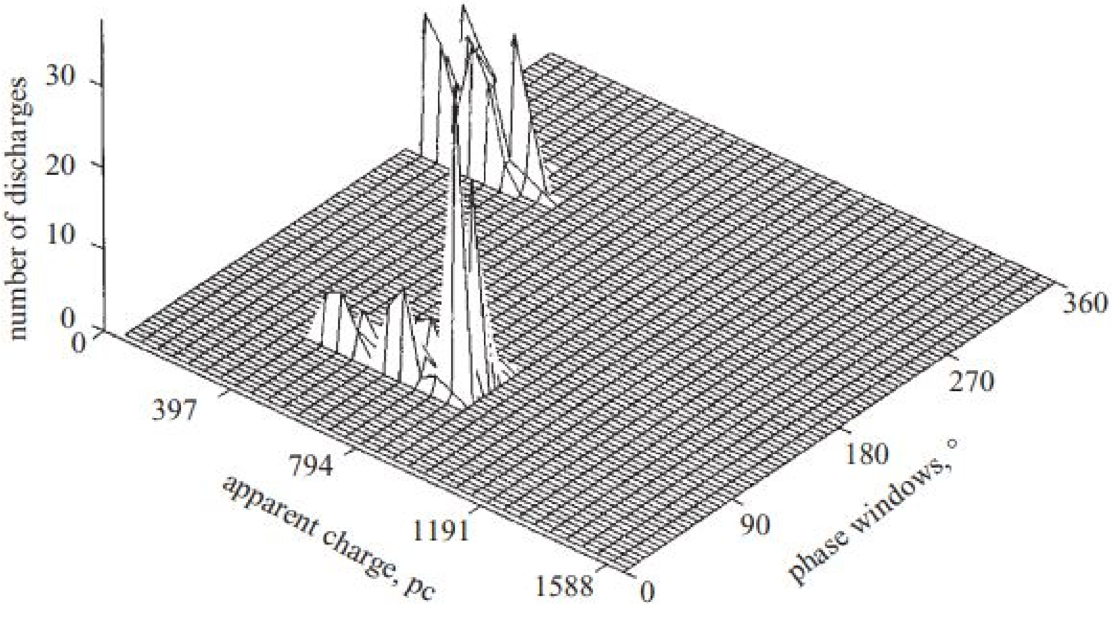


Figure 6.2: φ–q–n plot [58]

The obtainment of optimal results, however, is not as straightforward as this paper might indicate. The methods of obtaining discharge signals are vulnerable to interference and noise from elsewhere in the system or from within the same installation. These interferences can take the shape of the following: Various arcing generation from components, such as bolts, bearings and etc, PD activity from elsewhere in the system, corona generation, radio-waves and noise waves. In addition to haltering an optimal signal diagnosis, the monitoring is susceptible to poor choices based on the apparent signals given. The illusory apparent discharge, which required significant downtime and investigation, might just have been external interference from elsewhere in the system. This highlights not only the significance of ensuring the validity of measurement, but also the regularity of measurements, monitoring the progression and tendencies over time.

To minimize and prevent the influence of external interference the utilization of filters and re-directional circuits are essential in order to isolate the signals of interest [58]. The degree to which this effect is obtainable varies relatively much between measuring objects and the quality of the measuring setup. Normally, eliminating all possible interference is an unattainable practice. Hence the solution often lies in obtaining an overview of all potential sources of the signal present in order to account for them in the signal processing.

6.2.2 Electric loss measurement/Tan Delta

In theory, an insulating installation should ideally only conduct capacative current. Nevertheless, when the system experience losses, such as when experiencing PD, there will be presence of resistive current. An ideal capacitive system will have a phase angle of -90 degrees, e.g leading the voltage by 90 degrees. Resistive current is fully in phase with the voltage. The relation between capacitive current and resistive current is measured in tan δ, also known as the dielectric loss tangent. Meaning, when PD occurs in a system, a significant change can be detected in tan δ value. In other words, an increase in tan delta indicates an overall decrease in insulation resistance [58].

A voltage ramp test greatly illustrates the concept of tan a indicating PD activity. Ideally tan a will remain constant as increased voltage is applied, sudden spikes in tan a would indicate discharge sites reaching PDIV. Initial high starting values doe not necessarily indicate PD activity, but rather impurities and weaknesses such as faulty windings in the case of motors [58].

Tan delta measurement has broad utilization as a diagnostic tool which assesses the overall dielectric loss situation in plant items, being utilized on generators, motors, capacitors, CVTs, bushing and cables. Since PD measurements asses the overall dielectric loss of the given test object, there is an inadequacy of depth and detail in test results. The test will not with certainty identify the cause of dielectric loss, and neither accurately assess the distribution of weakness. Installations such as generators and motors can generally function with high amounts of dielectric loss. However if the weaknesses contributing to the high amount of dielectric loss are distributed disadvantageously, the insulation is drastically susceptible to insulation breakdown. Thus further and more specialized testing is advised.

6.2.3 Electromagnetic field measurement

Electromagnetic field measurement is a non invasive measuring technique detecting electromagnetic waves. Whenever PD activity occurs, electromagnetic waves are omitted, propagating away from the PD source. If situated inside some kind of enclosure, the omitted waves consequentially will propagate toward the confinement of the enclosure, e.g metal walls etc. The interaction between the electromagnetic wave and a earthed metal enclosure will result in a transient earthed voltage (TEV), which is detectable with the utilization of capacative probes [57]. The probes are placed in the opening, or rather in the gaps of the enclosure. As the PD wave propagates through the gap, the resulting TEV will be detected. The method acts as a straightforward basic entry detection methods. The possibility of measuring while the system is online and the non-destructive nature of the technique, makes it an attractive option for suitable installations.

The information extracted from these measurements are however limited. In order to obtain acceptable location accuracy several probes are required. Additionally this method is susceptible to substantial interfering by external signals. If excessively large, the interfering signals may invalidate the given results. As the capacative probe measures TEV, the potential interfering signals stem from voltage noise interacting with alternative metal object in the near vicinity. This includes bolts, batteries and etc.

As the method is a simplified approach, e.g with limited information and prone to interference, it is advised to further supplement it with specialized tests, granted a full depth diagnosis is needed.

6.3 Chemical Monitoring

All high voltage PD detection methods rely on measuring a quantifiable product of PD activity. While PDs result in electrical development and noise, they also alter the chemical composition in the given insulation medium, which as the name suggest is a main objective of chemical detection. Although principally applicable to most items of plant, chemical detection have enjoyed success and found its field of application in liquid insulated installation, specializing in transformer measurements. It has limited applicability in gas insulated insulation and is practically not applicable in solid state insulation [58].

As PD development occurs the chemical bonds undergo bond scission, resulting in the formation of gases [40] [12]. The energy required to break a given molecule bond, will be initiated by the energy released by PD activity. PD activity is normally a result of low dielectric strength in the liquid insulation. It’s important to point out that gas formation is not only limited to PD activity, but may also be a result of arcing and overheating. The weakest molecule bonds require the lowest energy value to break, which typically results in hydrogen gas. Stronger bonds require a relatively higher amount of energy in order to bond scissor, mainly depending on magnitude and development of PD activity, but will also be effected by other operational conditions determining the operational temperature. Thus the detection of gas molecules in insulation liquids will not only be a sign of PD activity, but also indicate the scope and deterioration of the activity, when the concentration of gases in ratio are calculated.

If sufficiently measured and calculated, the gas concentration may indicate which kind of faults are present, and hence prevent consequent repair costs and maintain stability. The method of detecting gases in liquid insulation is known as dissolved gas extraction(DGA)[127] . The principles of chemical detection can be read in [111].

There are two main approaches for chemical detection measurement: Laboratory testing and on-field measurement. For laboratory testing, oil extraction techniques are needed to obtain the required sample sizes. Normally 50ml will suffice. Regarding extraction techniques, there are several methods applicable to commercial measurement, but vacuum extraction is most common [58]. The samples are transferred to commercial testing in laboratories, which currently is one of the cheapest and most reliable methods. The gas measurements are conducted with the use of semiconductors, chromatography, miniature fuel cells and infrared spectrometers [58].

Commercially there are several techniques available for on-field measurement, known as fault gas detectors. These techniques utilize technology much similar to the aforementioned lab measuring techniques, where the main difference being that they are utilized on-site on plant items, especially on transformers. Currently there is a broad selection of commercially viable fault gas detectors, which covers the vast majority of transformer installations. Figure 6.3 illustrates a typical commercial fault gas detector

Figure 6.3: MSENSE® DGA 9 Fault Gas Detector [98].

Following the extraction of gas samples comes the crucial part of chemical detection: Data interpretation. The two data points evaluated are the quantity of a given gas, and the gases ratio relative to the other gases present in the sample. The current state of interpretation techniques is an example of progressive enhancement of measuring accuracy and a continuous evolution of the data basis. In it's infancy in the 1970s Dornernburg's used simple ratios to determine arcs, PDs and thermal faults, based on hydrogen, ethylene, methane and acetylene measurements. Dornenburg's method has subsequently been supplemented with Roger's ratio method, Key gases method and Duval Triangle method, which each in turn will be discussed briefly [127] [9].

6.3.1 Key Gas method

The Key gas method bases it's interpretation on the prevalence of gases in certain fault types statistics. Every fault type will have a certain profile based on the prevalence of each gas in the respective faults. For instance, partial discharges are low energy faults, majorly resulting in bond scission leading to the formation of hydrogen, with low prevalence of methane formation. Considering that the gas fault profiles are clearly distinguishable, samples, granted similar profile, should clearly indicate which type of fault has occurred in the insulation, but will not be a certain proof in insulation.

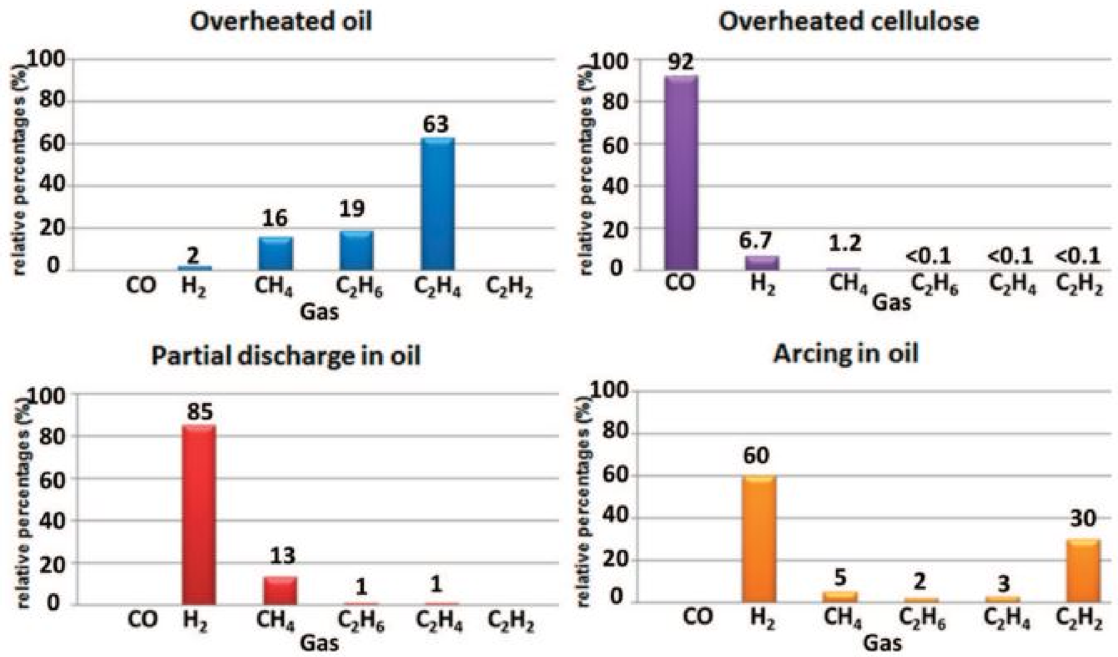


Figure 6.4: Key gas profiles for the four main gas fault types [9]

6.3.2 Roger's Method

An advanced version of Dornerburg's method, Roger's method, also known as the IEC standard, combines field knowledge and a wide data base to form a substantial fault diagnosis tool. Roger’s method consists of four ratios: C_2H_6/CH_4, C_2H_2/C_2H_4, CH_4/H_2, and C_2H_4/C_2H_6. The values of these ratios in combination are linked to a 9 diagnoses. In principle similar to the previously mentioned techniques, Roger’s method is more in depth and offers more specification in diagnose options, making it a favoured method in commercial chemical detection.

6.3.3 IEC Method

Similar to Roger’s ratio, the IEC Method bases its analysis on 3 of the same gas combinations, but excludes the use of the C_2H_6/CH_4 gas ratio. The exclusion of the ethane/methane ratio was due to despite detecting a temperature range, it does not further contribute to idenfication of fault type. Meanwhile it introduces the C_2H_2/H_2 ratio, aimed to detect potential contamination from on load tap changers [38].

6.3.4 Duval’s triangle

Duval’s triangle is a graphical interpretation strategy, utilizing the percentage of methane, ethylene and acetylene present in sample measurements. It offers a triangular map based on three axis representing the respective hydrocarbon gases [37]. The three hydrocarbon gases will, based on the percentage present, be given a triangular coordinate. The sum of these will result in a point within the triangle. The triangle is divided into six different areas, all representing a specific fault diagnosis, making it an attractive diagnosis tool.The layout of the triangle areas are based on relevant historical measurement data. The peril of utilizing Duval’s triangle is it’s inability to refrain from choosing a diagnosis. A sample from a transformer is not required to indicate the present of faults, nonetheless Duval’s triangle will offer a diagnosis.Thus it should always be tested for the presence of hydrocarbon gases before the consultation of Duval’s triangle.

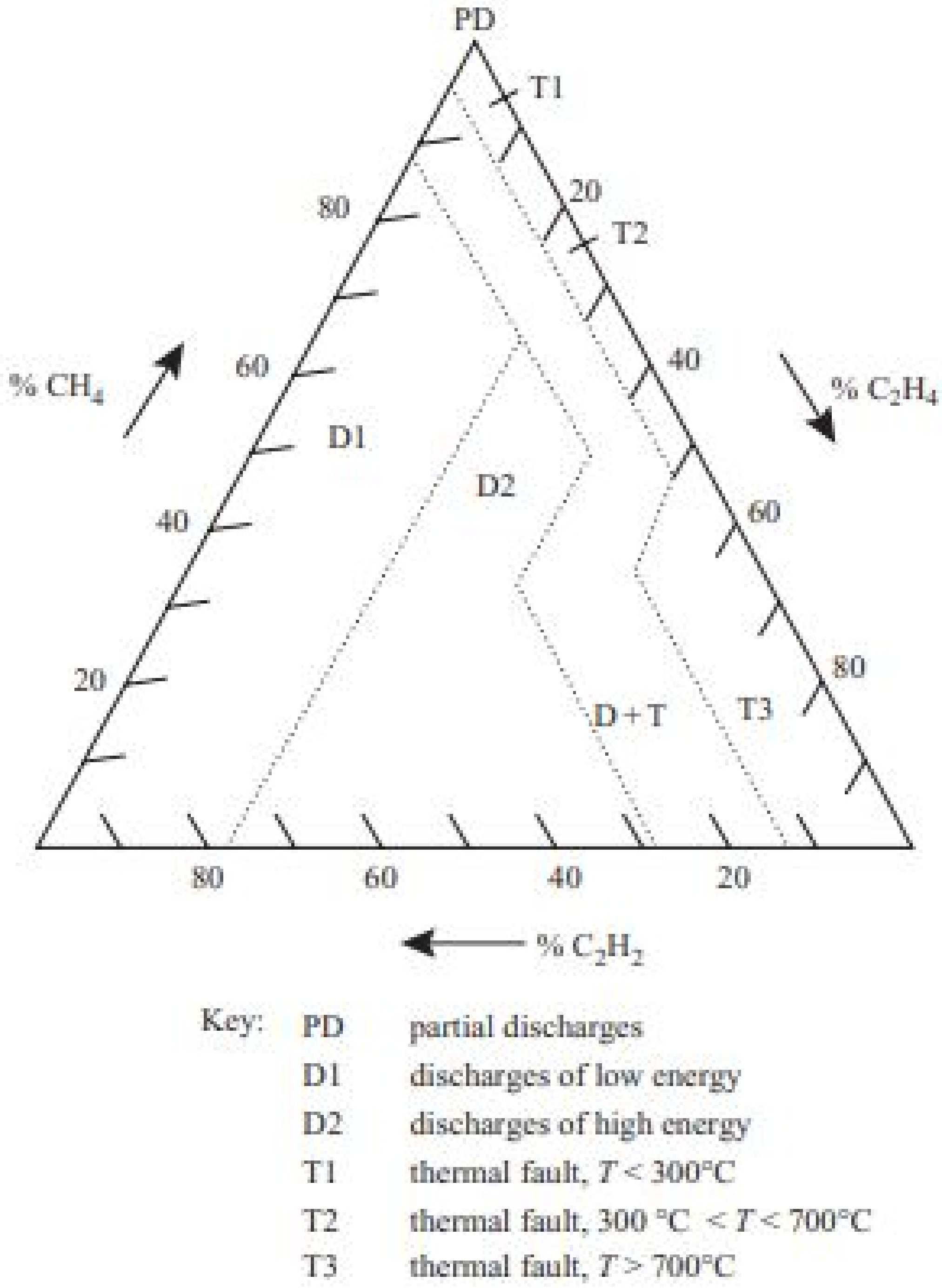


Figure 6.5: Duval's triangle [58]

6.3.5 Chemical detection summary

A study conducted in 2012 at the Curtin University, Perth, assessed the detection accuracy of the four aforementioned methods [3]. The study found that Duval's Triangle delivered the highest accuracy, while Key's Gas method delivered the worst accuracy. Roger's Gas Ratio and the IEC Method had nearly identical performance. The full results can be seen in table 6.1.

Method	Accuracy
Duval’s Triangle	72.0%
IEC	60.0%
Roger’s Ratio	58.9%
Key Gas	37.6%

Table 6.1: Accuracy of chemical detection methods [3]

6.4 Thermography

Partial discharges emit relatively strong heat compared to its surroundings. Modern thermal imaging technology is able to detect this thermal activity, and should in theory be applicable to most items of plant. However most items of plant, especially those with interest related to PD activity, are usually confined, e.g, either confined within metal construction or enclosed within solid insulation. This, combined with the inevitable thermal generation of plant items in operation, drastically limits the applicability of thermal imaging on solid state insulated installations. In regards to solid state insulated cables, thermography is considered as a ”healthy” option, as it is a non-invasive, non-destructive monitoring method, meaning that it can be conducted without temporarily turning off the system or physically interfering with the installation. Case studies have shown success for thermal imaging by the means of novel techniques in controlled lab environments, where faults near terminals have been induced [56]. However the applicability of thermal imaging on long distance underground cables is another practice, where the scope and accessibility are distinctively different. Even though the statistical knowledge of the probability of faults near terminals and accessories are known, other more viable methods are available.

Granted non-buried cable systems, albeit rare, thermal imaging will suffice as an easy accessible supplementary method for detecting anomalies. Detection of abnormal thermal activity may indicate high dielectric losses, and will thus be an alternative method in a fault location process, granted accessible cable sections or ground surfacing cable terminations. Thermal imaging applied on cable systems is also limited by the fact that not all cable defects have detectable thermal changes.

There is however a large potential in utilizing thermal imaging on non-enclosed installations, typically outdoor plant items, such as overhead lines, busbars and insulators. Thermal imaging is able to detect thermal activity inside installations and detects corona generation. Thermography applied on OHL and insulators can be seen in figure 6.6 Unfortunately the demand and interest of PD detection is negligible. Thus these applications are limited. A more in depth study on termography can be found here [139].

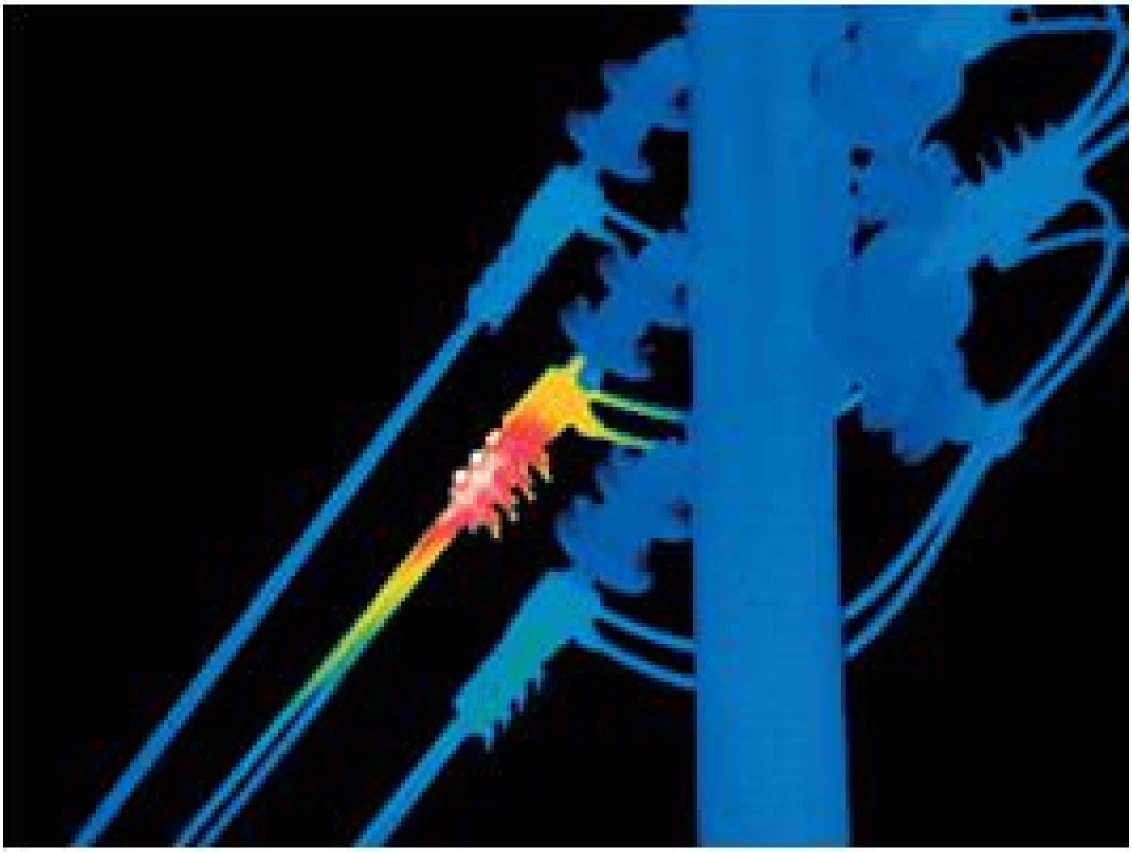


Figure 6.6: Thermography of overheadline and insulators [77]

6.5 Acoustic Monitoring

Versatile and cost-effective, acoustic detection is regarded as a viable alternative in the majority of plant items, but not on cables due to limitations in range [19][73], except when utilized in the closing stages of fault locating process. Sound omitted from electronic gear is usually associated with the sound of corona in overhead lines. However, PD also generates sound in form of acoustic waves, thus offering a detectable signal in a given medium. Detecting these waves with high accuracy is unfortunately a complex practice.

The material commercially used in acoustic detection, PDVDF (Piozoeletric Polymers), generates voltage proportional to acoustic force applied on the polymer material. When applied to a mobile probe, acoustic detection in its most elementary form can be regarded in the same practice as metal detectors, with the magnitude of the signal being proportional to the distance to the acoustic signal. A single probe approach is however a simplified approach and will only produce sufficient results at low voltage installations, where the relative low distance and non complex nature allows for a more linear approach. At high voltage plant installations the complex geometry, composition of materials and large dimensions severely reduce the usefulness, hence a multiple probe approach is necessary.

In larger installations in particular transformers, multiple probe method is applied. By attaching several probes to the earthed tank of the transformer, surrounding the insulation medium, coverage is provided by the virtue of various reference points. If assuming, homogeneous conditions and uniform acoustic velocity, the relative time pulses from the omitting PD source, when timed to each respective sensor, will be able to accurately locate PD sources. With the input of sensor positioning and time duration for pulse to travel the distance, a 3D plot can be generated with applicable software.

Ideal operating conditions with uniform acoustic velocity and simple geometry is however rarely the case, The majority of large high voltage plants have a complex geometry and a composition of several mediums, both interfering with the propagation of the acoustic signal. Provided a complex geometry, the omitted waves will spread upon surface contact and in addition getting absorbed by the surface material. This will effectively result in the signal arriving at the probes at differing times.

The following table illustrates the acoustic velocity of high voltage plant items [58]:

- Sulphur Hexafluoride (SF6) at 20 degrees 130 ms^{-1}
- Air 331 ms^{-1}
- Stainless steel 5800 ms^{-1}
- Transformer oil at 25 degrees 1415 ms^{-1}
- Polyethylene 1900 ms^{-1}
- XLPE at 20 degrees 1240 ms^{-1}

When the acoustic waves propagate through mediums with different velocity, the signal alters and the time spent in travelling poses a difficult calculation, as opposed to a uniform environment. The time required to satisfactorily locate PDs with this method in larger installations ranges from a few hours to a couple of days, depending of the complexity of installation and its given condition [58]. In smaller installations like bushings, capacitors and circuit breakers, a single probe methods will be sufficient.

On surface level, acoustic detection is applicable on high voltage cables, since the same principles as with other items of plant still applies. However, the need for the sensors to be in near vicinity of PD sources, effectively rules it out as viable option for an underground installation spanning several kilometres [90]. Granted the sensor is in close proximity of the PD source, sufficient results will ensue. This will however be luck-based, and will only be a viable option as an alternative method in the closing stages of a larger fault localizing process, which priorly has located the general proximity.

Acoustic detection in connection to generators and motors will not be discussed. Since these machines at operating conditions are significantly loud and noisy, the principle of detecting acoustic waves from PDs is inaccessible.

6.6 Cable Monitoring

As stated earlier, the applicability of test method on cables distinguishes itself from other plant items mainly by these three factors: Accessibility, length and complexity of composition. The subsequent methods and techniques discussed will all to some extent be applicable for numerous detection cases. The choice of method will thus be up to the user and should be based on merit, cable composition and assumption. In practice the subsequent methods will normally work in unison with each-other, with specialized tests supplementing periodic ”initiatory” tests. Initiatory tests include withstand tests and tan delta test, more specialized test include PD measurements and dielectric response methods, while fault locating methods may include TDR and bridge methods. In order to depict a typical full cycle monitoring of a cable accurately, the following chapter will be structured with the aforementioned progression in thought. DC applied voltage testing will discussed last. The subsequent discussed methods will contain traditional standardized methods with proven track record, and also newer non-standardized methods lacking wide acceptance within the field, but showing promise.

Before delving further into discussion of monitoring methods a brief overview of voltage sources will be provided, explaining the core properties they provide. The difference between AC and DC applied voltage have already been discussed.

6.6.1 VLF

Normally the impedance of a high voltage underground cable in operation is in the range of 50-60Hz, requiring a high amount of power to operate due to the large charge currents. However, if the frequency is significantly reduced, the power required is significantly lowered and the issue of large charge currents is eliminated. A decrease in frequency from 50Hz to 0.1 equates to 500 times lower power requirement. This would also result in large reduction in size of measurement system. The relation between power and frequency can be seen in the following formula. VLF can be conducted both sinusoidal and with cosine rectangular waveform [64].

$$P = 2pifCV2$$

6.6.2 Damped AC

Damped AC, also known as oscillating wave testing, is the concept of charging a test object to a predetermined level with an DC voltage source and then discharge the test objects capacitance via an high-voltage switch, resulting in a DAC frequency signal depending on the measuring objects capacitance [61]. DAC has especially showed great potential when utilized in PD testing. The test is typically conducted in the 20 Hz to 500 Hz range. The concept of DAC is illustrated in figure 6.7. The measurements are being conducted in the DAC voltage phase, detecting present PD signals and etc. Despite an initial DC applied voltage, the DAC method does not experience the negative repercussions of space charge. For more on DC applied voltage monitoring see chapter 6.8. The process of conducting a DAC test is straightforward. Due to the varying frequency of DAC, DAC can detect defects without exposing the cable to harm and represents a great overall detection utility, able to detect a numerous of defects. Due to the characteristic nature of DAC testing it is difficult to compare the results with those obtained with other AC voltage sources, additionally DAC do not fulfill the requirements of withstand tests as it does not provide a failure rate higher than those obtain at nominal operating conditions [28]. More on advantages and disadvantages of DAC can be found at [72]

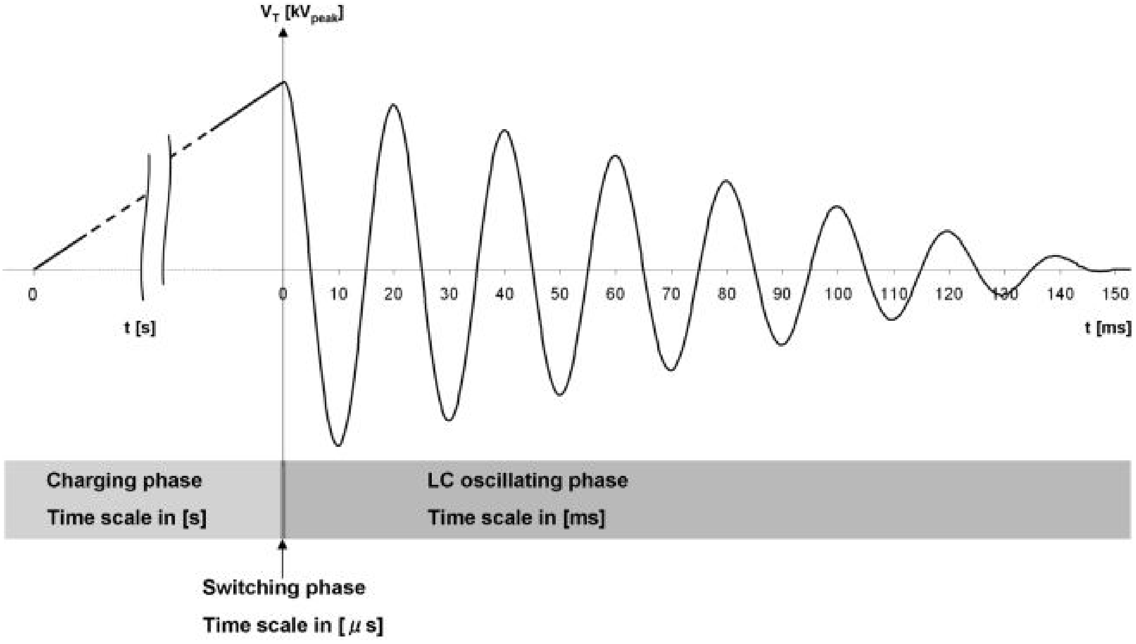


Figure 6.7: Schematic overview of the three different stages of DAC applied voltage [72]

6.6.3 Resonant AC

The term resonant AC refers to offline AC applied voltage testing. Resonant AC testing should not be confused with online applied AC voltage. While online AC applied voltage is required to utilize operating voltage at 50/60 Hz, offline resonant have the liberty to regulate voltage level, typically in the range of 20 to 300 Hz.

6.6.4 Voltage withstand tests

Voltage withstand testing refers to initial tests conducted to assess the overall dielectric strength of a cable by voltage stressing it at different voltage levels. If the cable experience failure during the test, the cable effectively fails the test. Simple withstand test have straightforward premises, while monitored withstand tests are more sophisticated as they supplement with specialized tests. Overall withstand tests are the most utilized cable diagnostics [20].

6.6.4.1 Simple withstand test

By applying elevated voltage levels to a cable in offline conditions, typically 15Uo-3Uo, a simple pass or no-pass diagnosis can be determined. If the cable displays no failures for the full duration of the test, the test is considered passed. If the cable displays any type of fault occurring during the full duration, the test is not passed. This is normally followed up by appropriate measures and cable repairment. The test can also be conducted online, but is discouraged due to the inability to elevate applied voltage, inferior results and repercussions in the cable systems if cable fault occurs. Similar tests are applied on cables during manufacturing and the pre-deployment phase. Unlike the majority of cable testing, withstand tests are not opposed to the eventual outcome of cable failure, as one of the main purposes of the test is to stress a cable exceedingly in offline conditions rather than risking potential failure of the cable during service. Hence the tests are normally coordinated with standby repair procedures [1].

Neetrac considers the three following elements to be part of a simple withstand test [28]

- A defined voltage exposure: The applied voltage should be distinguishable rms, magnitude, number of cycles, duration etc.
- A repeatable voltage exposure: The applied voltage should be repeatable on cables with similar characteristics
- A well defined failure rate: The failure rate during a simple withstand test must exceed the failure rate experienced during nominal operating conditions.

The most common method is to utilize VLF 0.01-0.1Hz sine and cosine waveform. The utilization of VLF techniques have grown popular across the majority of cable testing methods, which is also the case for simple withstand testing. Traditionally the utilization of DC applied withstand testing was common practice. The test equipment is small, and is applicable on long distance cables, thus solving an issue AC applied voltage testing struggles with. All DC applied voltage testing does however lead to the problematic issue of trapped space charge, potentially leading to fatal breakdown when cables are reinstated in service, effectively ceasing the utilization of DC withstand testing long term.

Resonant AC applied testing is also utilized with good results. The use of RAC has increased significantly in the last 30 years. The major drawback is costly and large testing equipment. The potential utilization of Damped AC voltage in simple withstand testing has been widely discussed within the power industry. The current flaw prohibiting the potential utilization of DAC is the techniques inability to generate sufficient breakdown voltage in order to initiate the stressing of faults present[72][28]. Figure 6.8 shows an overview per 2014 of the utilization of each simple withstand tests in North America provided by Neetrac [28].

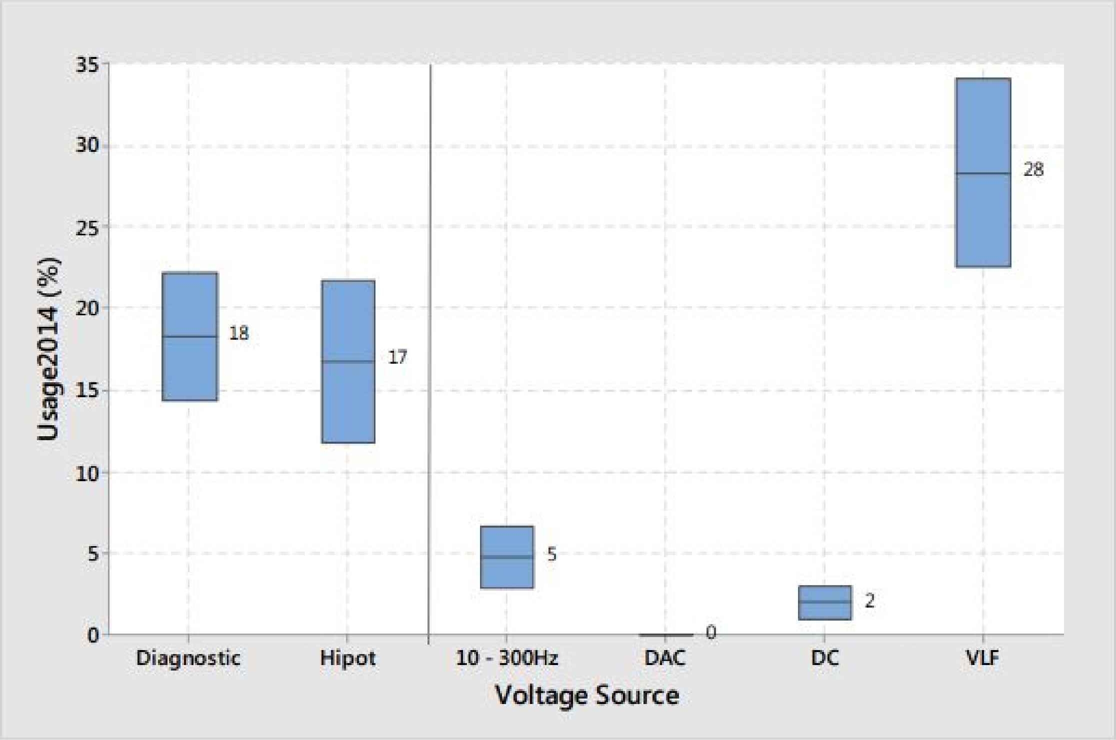


Figure 6.8: Type of voltage source for simple withstand testing in North America [28]

The figure shows that VLF is most utilized method of simple withstand testing.

The utilization of simple withstand test is decreasing, as the more in depth sophisticated version of monitored withstand test are preferred. This is due to sparse information gathered from Simple Withstand test and the black and white diagnosis it provides.

6.6.4.2 Monitored withstand test

MWT is the principal of supplementing withstand test with additional specialized test focusing on dielectric properties of the cable, thus providing a more in depth assessment of the condition of the given cable. Typical test supplementing the initial withstand test are tan delta measurement and PD testing. DC leakage current and DAC have also been utilized in combination with simple withstand test, but DC leakage is advised against due to the issues related to trapped space charge.

The test consist of a ramp up phase, energizing the cable step-wise to predetermined withstand voltage, a hold phase with set duration in order to assess properties and lastly ramp down phase de-energizing the cable. By simultaneously monitoring the withstand properties and dielectric characteristics of the cable, the test conductor will gain valuable information on the health and ageing characteristics of the cable, possibly uncovering major defects presents that would have gone undetected in a simple withstand test.

In addition MWT improves upon the passing criteria providing it nuance, adding on provisional pass and no-pass criteria. Neetrac provides the following conditions, granted detected, that makes a cable not pass the criteria [21]:

- 1: Dielectric puncture.
- 2: No dieletric puncture but irregularities and non compliant measurement:

IEEE defines a dieletric puncture as: ”A disruptive discharge through the body of a solid dielectric and resulting in permanent loss of dielectric strength” [65]. If no dielectric puncture occur, but the measurement display irregularities, e.g high magnitude, sudden spikes, instability and steady moderate increase of measured parameter, the measuring object will not pass the test.

6.6.5 PD cable monitoring

The partial discharge mechanics have been previously described. The current state of the art PD monitoring have progressed to the point of being able to accurately diagnose partial discharges in cables, with different material, voltage rating and at different points of the cable life cycle. If a an aged cable display fatal high levels of PD activity, the test conductors may with high certainty predict an inevitable breakdown. Likewise a healthy newly manufactured cable with low PD measurements would indicate longer lifetime. However as cables age and reaches the middle part of the ageing spectrum the assessment of further progression gets challenging. Currently there are no standardized methods for PD testing, but there are several methods recommended. The concept of partial discharge measurements is described in detail in IEEE 400.3: ”IEEE Guide for

Partial Discharge Testing of Shielded Power Cable Systems in a Field Environment" [70].

An essential part of the enhancement within the field of PD monitoring, of course in addition of enhanced detection techniques, is the knowledge and historical data assessed on the nature of PDs, cable manufacturing and electrical stresses. However the current knowledge of PD is frankly insufficient to satisfyingly operate and maximize the potential of both extruded, filled and paper cables. Assessments of singular cables may prove accurate if sufficient knowledge of the cable is present. However the ability to generally predict the lifetime of manufactured cables proves challenging. For instance the use of accelerated age test may yield vastly different results, despite apparent similar conditions. The complexity of a manufactured cable combined with the unique stresses a single cable experience during service simply makes the accuracy of prediction average at best.

IEE 400.3 [73] list the following parameters measured in typical PD test.

- PDIV
- PDEV
- PD magnitude measured in (q).
- PD repition rate measured in (n).
- PD phase angle $\Phi i = 360 (ti/T)$
- PD $n\Phi q$ plot
- PD magnitude vs. voltage plot

As the concept of electrical PD measurement is already discussed, the subsequent discussion will rather focus on PD localizing of cables.

6.6.5.1 Type of Test

There are two main approaches when engaging in PD measurement, off-line testing and on-line testing. The glaring reasoning for online measurement is the matter of not being required to detach the cable from operating service. In addition to disadvantages of detaching parts of a power grid, the time consumed and cost of conducting off line tests are high. This is a delicate matter concerning the monitoring of underground cables and especially sub-sea cables. Online measurement does however yield alternative results frequently sought after, and in some aspects superior results. This is especially prominent when it comes to PD localizing.

Separating the two approaches in regard of testing conditions is first and foremost the ability to regulate applied voltage. While conducting online PD test, the voltage is already present and the cable is energized, thus PD activity is present, granted PDIV lower than the current system operating voltage. If PDIV is achieved, certain PD activity sites are self-sustained and require the necessary de-energizing duration. In the case of conducting an off-line test, the test conductor needs to assure the re-ignition of PD defects present. An applied test voltage of 1.5 Vo for a couple of minutes should ensure proper energizing of the system [73] [27].

6.6.5.2 Online Measurement

The cable remains connected to the system at both ends. The measuring setup is connected to the cable via a number of capacity couplers or to current transformers. The devices are both tasked to detect transient discharges signals emitted from present defects. The obvious advantage is that while conducting online testing, the cable is measuring during nominal operating voltage and nominal operating temperature, and is overall simple to conduct. The disadvantages are the following: Inability to sufficiently regulate applied voltage, e.g unable to detect PD with PDIV over nominal operating voltage, only offering the applied voltage type the system operates with, typically 60 Hz AC. It requires multiple sensors at each cable accessory and lastly the test cannot be conducted in combination with other tests such as withstand tests. The IEEE IEEE 400.3 provides the following advantages of off-line PD monitoring: PD measurements can be extracted under different loads, which aids in the identification process of certain defects. It also notes the advantage that the test do not result in system outage.

6.6.5.3 Offline Measurement

The cable is detached from the system. One end, the choice is arbitrary, is connected to a coupling device and the voltage source fitted for the test. The other end is left disconnected, e.g short circuited. Alternatively two sensors can be connected to each end, enhancing the sensitivity at long distance cable testing. The couplers are connected to a specialized test circuit. The test circuits are unusually analogous for on and offline testing. Offline tests can be conducted with a variety of voltage sources (DAC, VLF, and RAC), providing a healthy basis of alternatives. The drawback of offline methods are their increased cost, complexity and difficulty with comparisons against operating values and overall insufficient track record of methods. The IEEE Std 400.3 ”Guide for Partial Discharge Testing of Shielded Power Cable Systems in a Field Environment” [70] list the following advantages for offline PD testing: The ability to detect both PDIV and PDEV and the ability to detect PD characteristic at different voltage levels due to the regulated voltage source.

6.6.5.4 Localizing PD

Localizing PD is arguably the most crucial part of PD monitoring. Without being able to accurately locate fatal PD activity, the work of restoring faulty cables turn into a strenuous task, especially considering the fact that the majority of cables in transmission are underground, with the most crucial cables situated subsea. Granted significant cable length, non sufficient accuracy will be the cause of an substantial increase in financial costs, both in repair costs and loss of power flow. In addition non-optimal accuracy may be the difference of months of down time, due to fault localizing.

There are two commercially applicable methods for locating PD faults: Time measurement of discharge pulses and frequency measurement. These methods are sometimes referred to as cable mapping.

6.6.5.5 Time Domain measurement

Time domain measurement of cables is usually setup as offline test, but may be conducted as an online test with fitting sensors applied. The method applies the concept of reflectometry. Whenever PD activity occurs in a cable, the discharge site emits a discharge pulse propagating in two directions. Since the pulse reflects at the short circuited side of the cable two separate signals can be measured at the connected end. Granted the length of the cable is known, the relative arrival of the discharge pulse can be calculated into the relative position of the discharge activity. The method does however struggle with achieving sufficient accuracy, as with acoustic detection and other signal based detection techniques. The propagating path for the signal is not necessarily uniform, the signal may be interfered or the geometry of the installation may obstruct the ideal path between the source and the measuring device.

The term attributed to signal propagating in cables is cable attenuation. High attenuation results in a decrease in detection accuracy, by decreasing the amplitude of the signal and increase the width, thus the duration of the signal. Hence there is a risk with high attenuated cables that the measures are not able to detect signals, and if detected the location is non-accurate. Generally aged, mixed and long cable system experience high a attenuation. Aged cables usually contain physical abrasions, heavy moisturising, low neutral size and high level of electric noise. Mixed cable systems, usually due to replacements of cable parts, contain transitions in propagating due to impedance difference of the disparate cable part, in addition the number of splices associated with repaired cable systems adds to the impedance variation. Due to the aforementioned conditions, increase in the length of cables generally results in lower sensitivity and accuracy. An optimal test setup, calibration and experienced test conductors will to some degree mitigate these effects. However the negative repercussion due to non-optimal cable condition proves difficult to mitigate [70].

6.6.5.6 Cable data

A crucial part of ensuring optimal test results is to gather as much relevant information on the given cable. IEEE recommends contacting the cable manufacturer, surveying for relevant information, e.g asking for test results on the specific cable, and test data on corresponding cable types. The manufactured test could indicate the nature of the cable, especially aging tests. Aging test may however be inaccurate, due to the discrepancy between test conditions and service conditions. To supplement aging test, historical data on operating conditions, granted available, should be reviewed in order to assess cable aging. Relevant data on associated accessories should also be provided before conducting PD test. The composition of the cable system, cable types, age, splices and etc should also be taken into account. In addition to a collection all relevant data, preliminary testing will be beneficial. These steps will base the foundation for good decisions and calibration.

6.6.5.7 Frequency domain localizing

As with time domain based measurement, frequency domain testing can also be conducted both online and offline. The frequency of the emitted PD is measured by sensors. A discharge will have different frequency components, but is generally in the range of a few hundred kilo Hz to 1 giga Hz. The frequency signal will depend on the distance between discharge site and the measuring sensor. The location of the PD is determined by measuring the frequency of the signal with the energy measured. To obtain sufficient accuracy IEE 400.3 [70] recommends the utilization of high bandwidth sensors and short distance intervals between senors, with a recommend 150 meters as maximum distance.

6.6.6 Tan delta measurement

For tan delta measurement of cables VLF is the preferred voltage source. VLF allows a significant reduction in size of the testing instrument, effectively making it possible to have a portable setup for on-field measurement. It’s also been showed that low frequency measurement is significantly more sensitive [26][1]. One of the advantages of tan delta measurement is that it does not depend on the geometry of the measuring object. Tan delta measuring will not in itself locate specific sites of PD activity or other defects, but rather indicate PD activity, as tan delta is addressing dielectric losses of the entire measuring object. As aforementioned, PD activity is not the only source of dielectric loss in a cable. In a typical XLPE cable the following reasons for dielectric loss are found: PD activity, water treeing, electrical treeing, moisture at terminations, corrosion of metal sheath and poor contact between the layer of metal sheath and insulation shield. Figure 6.9 displays the concept of tan delta in cable insulation.

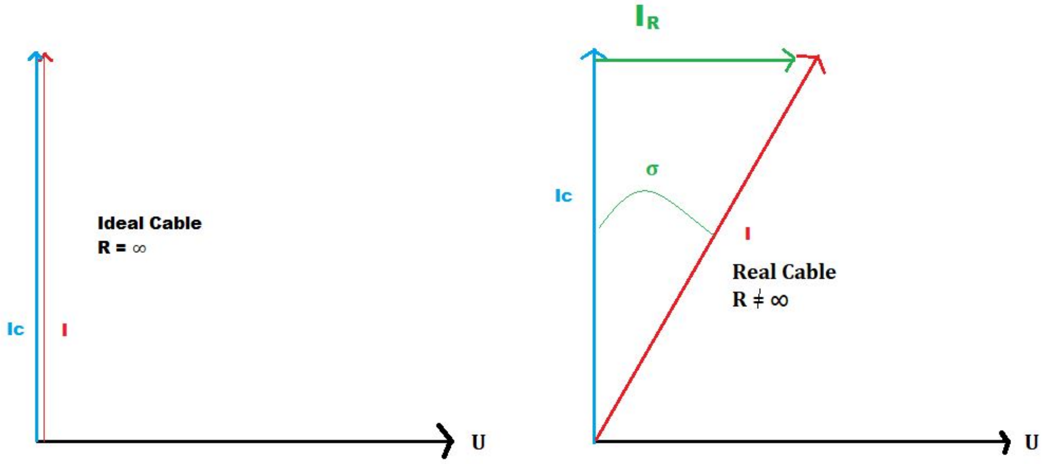


Figure 6.9: Tan Delta of ideal cable and for a typical operating cable

Since tan delta cannot in itself locate PD activity, PD measurement should be implemented alongside. Since both tan delta and PD measurement use sinusoidal measurement they can be combined simultaneously along with VLF tests to obtain a larger overview of the cable health. This will be discussed in a subsequent shortly.

The main principle of VLF TD testing is voltage ramping and voltage holding. The applied voltage is given in the unit of U0, referring to phase-to-ground operating voltage. The purpose of the testing is to ramp the applied voltage up to a value higher than normal operating, usually 2Uo, and then maintain or hold the voltage for a significant duration, testing if the cable withstands without experiencing gross breakdown. At the same time information is extracted.

A typical VLF TD usually consists of the following measurements:

- Tangent delta (VLF-TD)
- Differential tangent delta (VLF-DTD)
- Tangent delta stability (VLF-TDTS)

Tan delta is measured at 0.5 U0, U0, and 1.5 U. Differential tangent delta is defined as the differential between measured TD at 1.5:

$$DTD = TD(1.5U0) – TD(U0)$$

Tangent delta stability is obtained by measuring TD at Uo over set duration, getting the TD mean over the given duration, which in turn undergoes a standard deviation calculation.

The relevant voltage levels will then be 0.5 Uo, Uo and 1.5Uo. This is the standard for VLF TD measurement, but deviations from the norm may occur. If aged service cables indicate gross levels of deterioration at 0.5Uo, further voltage ramping may be deemed unnecessary to protect the cable from further stressing. The recommended number of measurements are 6 at each voltage level with a 10s interval.

TD testing is simple and straightforward to conduct. The challenging part reveals itself while interpreting the measuring results. As TD provides an overview of the total dielectric loss of the cable, and not focused points of dielectric losses, a wide range of solutions reveal themselves. Granted significant tan delta values, supplementary narrowing tests will be beneficiary, but not necessarily cost effective. IEEE Std 400.2-2013[2] provides guidelines for further recommended choices of action based on the three aforementioned parameters. The reference values for XLPE cables are shown in table 6.2 and 6.3

Condition assessment	VLF-TDTS Uo		VLF-DTD Uo		VLF-TD at Uo
No Action Required	<0.1	and	<5	and	<4
Further Study Advised	0.1 to 0.5	or	5 to 80	or	4 to 50
Action Required	<0.5	or	> 80	or	>50

Table 6.2: Reference Values for aged XLPE cables[2]

Condition assessment	VLF-TDTS Uo		Tip Up (2Uo-1Uo		VLF-TD at Uo
Acceptable	<0.1	and	<0.8	and	<1.0
Further Study Advised	>0.1	or	>0.8	or	>1.0

Table 6.3: Reference Values for newly installed XLPE cables[2]

IEEE has set reference values based on historical merit. As this paper focuses mainly on XLPE cables, only these are included. For tan delta reference values for other extruded and lamited cables see [2] The following courses of action are presented in [2]:

- No action required
- Further study adviced
- Action required

No action required
TD values are below a certain value, indicating low dielectric loss in the cable. The probability of high localized stress is also quite low. Cable is recommend to be reinstated into service, but a periodic retest of the cable is advised.

Further study advised
The results are inconclusive. The results are of relative high value and indicate a substantial amount of dielectric loss across the cable, however not exceeding the level required to classify it in the action required category. Still the result may indicate fatal locations of insulation loss, thus further testing is advised. The recommended further steps are PD test, withstand test and visual inspection of accessories. Considering the wide range of value within this category, the test values' relative position to the limit values should indicate the severity of dielectric loss present.

Action required
The measured TD values are extremely high and indicate gross dielectric loss within the cable. The next step usually consists of either an immediate replacement of the cable or withstand testing it, triggering it to breakdown with subsequent repair.

In addition to the recommended courses of action, the values ratio to each other might also indicate the type fault present. This should however not be interpreted as actual ”evidence”, and supplementary specialized test are needed.

An evident weakness with the TD measuring method is its inability to take into account the length of the measuring object. An exaggerated example will be provided to emphasize the point. A 10 metre cable with faulty accessories will experience overall high tan delta measurements despite low dielectric loss in the cable itself. However if the cable length was increased to 1 km provided the same faulty accessories, the overall tan delta would indicate low overall dielectric loss, despite the same potential of vital local faults. A solution lies in plotting cable length with tan delta results. The corresponding plot would indicate the nature of loss in the given cable. If the plot is increasing, e.g tan delta increasing with cable length, the results would indicate problems with cable construction such as metallic shield corrosion. A downward slope, e.g a decrease in tan delta with length, would rather indicate faulty accessories and portion of the cable with high dielectric loss. Analyzing tan delta relative to cable length will also be attributed to the increased data base of cable measurement results, which in turn enhances the knowledge needed to take good interpretations.

Summarized, TD measurements offer a low-threshold measuring method with excellent overall assessment of insulation loss indication. Used as a first step in cable measuring testing, TD with supplementary specialized tests will with relative high probability gauge the nature of dielectric loss present. However the results are limited from accurately specifying the nature of the insulation deterioration. Together with the vast majority of tests, PD measuring also requires the removal of cables from installation, emphasizing the challenge of online monitoring.

6.6.6.1 Combined PD and Tan Delta Measurement

The argument for a combined simultaneous monitoring of tan delta and PD can be divided into three parts: Time, knowledge and stressing. The time saved by conducting the tests simultaneously represent significant financial benefits, as well as maintaining power stability by reinstating aged installation quicker. Essentially the test setup is quicker and the duration is relatively short compared to traditional methods, since the faults and locations are located more swiftly. Test equipment manufactures estimate total test duration and testing costs can be saved ranging from 50% to 75% [15].

Excessive testing on cables, especially aged service cables, may lead to redundant stressing of the material, which if preventable is desired. This desire should not be misconceived as an acceptance of lower thoroughness, but rather a desire for increased effectiveness. On the contrary, simultaneous testing may prevent reinstating severely faulty cables into services. A hypothetical example of this would be testing conducted on an aged XLPE MV cable. A tan delta VLF test is conducted, with values indicating overall insulation degradation. However the cable does not experience breakdown at voltage withstand test with long duration intervals. Based on this, reinstating the aged cable may seem a sensible solution. As mentioned, tan delta provides the average dielectric loss of the whole cable system, including accessories. Hence PD discharge sites if undetected may still be present with high PDIV, which eventually leads to cable break down if reinstated in service. It should of course be mentioned, that the norm procedure is to conduct supplementary PD test, granted significantly tan delta is measured. Nevertheless this again only emphasis the need for simultaneous testing.

Along with the continued enhancement of monitoring techniques, the information related to the respective tests have increased accordingly. IEEE provides standards, consisting of detailed instructions and reference values for the respective test conducted. With the extension of available IEEE standards, not only do the guidelines enhance in depth, but in addition they will to a greater extent enable more personal to conduct tests. Bases on the drive towards effectiveness within the field, it is not far fetched to expect a standardization of simultaneous PD and tan delta testing in the future.

6.6.7 Dielectric Spectroscopy

Dielectric Spectroscopy is similar to Tan Delta measurements as they both assess the overall dielectric health of a measuring object by measuring the real and imaginary components of the cable. DS, also referred to as impedance spectroscopy, measures the dielectric properties as a function of frequency [88]. The frequency range applied in

Dielectric Spectroscopy is usually in the range of 0.001 Hz to 100 Hz [1]. DS provides substantial information due the wide frequency range applied. Since tan delta inversely increase with frequency, the measured tan delta values are highest at low frequency, allowing for VLF testing. The strength of Dieletric Spectroscopy can be a weakness, as the vast amount of data extracted may pose challenging to interpret and analyze, requiring skilled test personnel.

DS can also act as non-destructive/non-invasive method when applied as a broadband dielectric spectroscopy [75]. The non-destructive nature of DS combined with the detailed information it provides, makes it an attractive method forwards. DS have experienced drastic improvement in recent years and provides broad utilization also in food chemistry and medicine [34].

There is however drawbacks to DS measurement of cables. Neetrac and IEEE Std 400™-2012 both discuss these disadvantages [1] [22]: Long test times are required at each voltage level. There is a risk of trapped space charge, it is unable to detect discrete defects and there is no established pass/fail criteria currently.

6.7 Fault location techniques

The prominent peculiarity of high voltage cables compared to other items of plant, is the vast scope of the installations. Motors, generators and transformers can be large installations, but the fault location is restricted within a manageable vicinity. Having knowledge of the magnitude and number of discharges are of relative low value in regard to repairment unless the location of them are known. It is worth noting that the extent of faults are not limited to just dieletric defects, but may also be faults of mechanical nature. If a long distance cable experiences faults, the fault can also be located in the accessories of the cable system. IEEE Std 1234™-2019: ”EEE Guide for Fault-Locating Techniques on Shielded Power Cable Systems” [71] go in great detail discussing the methods conventionally utilized in fault locating.

Fault location of faults in cable systems can be divided into two main groups: Pre-location techniques and fault pin-pointing techniques.

Pre-location techniques:

- Conventional time domain reflectometry
- Surge arc reflection method
- Impulse current method
- Burn arc reflection method

- Decay method voltage coupled
- Bridge methods

The majority of pre-location techniques utilize the concept of TDR: Surge arc reflection, Burn arc reflection, Impulse current method and Decay method all utilize the concept of TDR. The other methods are referred to as bridge methods.

6.7.1 TDR methods

TDR methods utilize conventional TDR measuring techniques combined with signal source designed to stress, or rather activate the present fault, forcing a discharge signal measurable by TDR measurements. This is usually done by connecting a surge generator to the measurement circuit. Surge generators are high voltage capacitors aimed to initiate, or rather thump the fault. The surge generators require sufficient voltage and energy in order to properly thumb the fault. The surge generators are isolated from the TDR via a coupler, preventing HV surge short circuiting the TDR signal. A typical set up for TDR method can be seen in figure 6.10, displaying the set up for a surge arc measurement test.

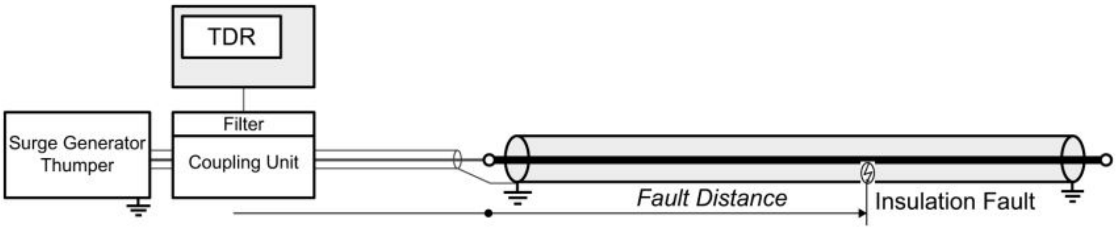


Figure 6.10: Schematic overview of Surge arc reflection [71]

Bridge methods

Bridge detection methods utilize DC applied voltage circuits, where unfaulted conductors are connected in a bridge circuit with the faulted conductor. A galvanometer is utilized connected across the faulted and unfaulted conductors. By adjusting variable resistors in the circuit the galvanometer will reach null. If the length of the conductors and resistance ratio is known, the location of the defect in the faulted conductor may be calculated. The most conventional bridge methods are Murray bridge method and Glaser bridge method.

Pin-point techniques

Pint-point techniques are utilized in the closing phase of fault locating process. When conducting TDR on a cable a relative location of the fault may be provided as a result. If the result is of low accuracy, further locating will be a strenuous task. However, even if the TDR yields result with high accuracy, further pin-pointing may still be required. Pin-pointing the fault location is based on transmitting a signal into the cable thumping the fault and subsequently detecting the signal emitted from the fault site. The two most conventional methods are acoustic detection and electromagnetic detection. The fault site will emit an audible thump when the transmitted signal reaches and triggers the fault, which can be detected by personnel operating an acoustic detector. The method is currently the go to method and do not require a skilled operator. The electromagnetic approach is more advanced and is based on tracing the direction of current. By dividing the cable into segments while trailing the current, the faulty segment may eventually be located. The method requires skilled operators.

6.7.2 Submarine conditions

The method of fault locating in submarine conditions vastly differs from those conducted ashore. Due to the inaccessible nature of submarine cables conventional pin-pointing fault location techniques are near impossible to conduct. Additionally subsea cables are often of significant length, mitigating the accuracy of conventional TDR methods due to signal attenuation. Due to the presence of water the fault arc is extinguished [71]. This prevents TDR methods like surge arc reflection which relies on thumping the fault arc. Fault locating in submarine conditions required expertise personnel and is regarded as specialist field. It is not without reason that submarine faults are the most substantial in regards to outage duration and subsequent financial repercussions. For more on the specialist field of subsea cable fault locating, see [63][84].

6.8 DC applied testing

Initially testing of AC cables were conducted with applied DC voltage. DC voltage where applied in order to withstand test cables, testing when and how breakdown occurred at ramping levels. This method is also known as direct voltage high-potential test method, or rather DC hipoting.

When polymer cables where phased into the power grid, the main method of testing was by DC. In service, the brand new polymer cables experienced an unexpected amount of failures [24] . As discussed, a large portion of this can attributed to the then undiscovered perils of water treeing. Eventually the uncharted failures where attributed to the phenomenon of trapped space charge. Unlike AC, the DC field only travels in one direction, hence resulting in unequal migration of space charge in one direction. If defects where present at the time of testing, which they unfortunately unavoidably are, the space charge gets trapped within these defects, effectively decreasing the BDV of the defects. After being reinstated in operation, the cables will experience an increase in breakdowns failures due to the now decreased BDV [122].

In modern testing AC applied test are preferred. Although DC testing offers a solution to the problem of charge current present in high frequency AC testing, VLF AC testing is still preferred, due to the aforementioned issues related to space charge, in addition to the fact that DC testing is unable to detect insulation defects at the same level as AC applied voltage testing [2].

6.8.1 DC Leakage

DC leakage is DC voltage applied testing which assess the overall health of the cable insulation [22][110]. Ideally conductor insulation will have resistance, preventing the potential leakage of current. As the insulation progressively ages, the resistance decreases, becoming increasingly conductive, e.g resulting in the leakage of current. The ageing process combined with the increased capacitance with cable length, allows for large amounts of leakage.

In order to measure the leakage current, a DC voltage is applied between the insulation shield and conductor. The cable should be sufficiently de-energized prior to voltage ramping. As the voltage is ramped up, each interval will have to reach its steady state value prior to leakage current measurement. The method is susceptible of the unwanted consequence of DC induced trapped space charge.

6.8.2 Recovery voltage

When a fully energized voltage applied cable is suddenly short-circuited, the resulting open circuit voltage measured across the circuit is known as the recovery voltage [96]. The resulting voltage increase after short circuiting is due to trapped space charge being released. As space charge tends to get trapped in defects, the volume of the measured recovery voltage provides a general assessment of overall cable health. This especially applies to trapped space charge due to water moisturising, hence recovery voltage measurements being a preferred method for indicating the presence of moisture [22].

Recovery voltage testing is conducted by applying a DC voltage to a cable fully charging it. Typical charging time is 15 minutes. By utilizing a ground resistor the cable is then discharged, typical duration of 2-5 seconds. The recovery voltage is then measured, often referred to as Recovery Voltage Measurement (RVM). The maximum recovery voltage is noted after the necessary rise time. Noting the measured voltage after significant decay time is also beneficial in order to assess the nature of the recovery voltage. Figure 6.11 shows the concept of recovery voltage.

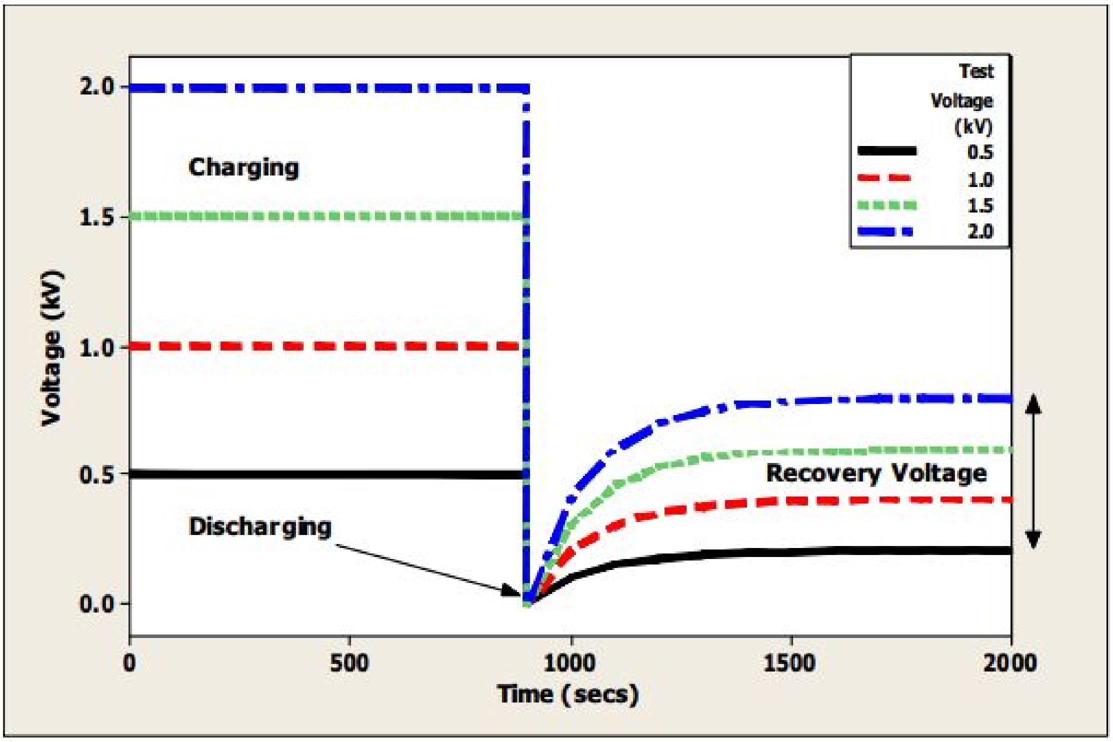


Figure 6.11: Schematic overview of recovery voltage method for different voltage rating [22]

To determine the overall health of the cable the Diagnostic factor (D) is utilized. The Diagnostic factor is defined as the ratio between 2 Uo and U. Thus in theory a new healthy cable would ideally give D value of 2, showing a linear relation between recovery voltage and increased charging voltage. As the health of the cable deteriorates, the relation becomes non linear and the value of D will increase, hence elevated D values indicates decreased cable health.

The following table 6.4 explains the recommended further courses of action based on measured Diagnostic factor:

Diagnostic Factor (D)	Evaluation	Recommended Action
2.0-2.5	Insulation in good condition	No action
2.5-3.0	Insulation in fairly good condition	Further study advised
>3.0	Severely damaged	Replace cable

Table 6.4: Interpretation rules for measured Diagnostic Factor [22]

As it currently stands, RVM is considered a niche alternative, e.g viable, but other techniques are still preferred. The method is attractive because of the overall assessment it provides and the simple nature of the measurement process. The concerns related to trapped charge due to applied DC voltage is significant, and thus, granted RVM is chosen, the user must carefully enforce proper discharging after each test. Since each cable type have its own specific recovery voltage properties, the applicability of RVM is limited to uniform cable systems, e.g non-hybrid systems.

6.9 DC Monitoring

As previously mentioned DC technology and thus DC monitoring have been allocated far less research. The research have however experienced a significant increase in the last decade. As the dielectric properties of a DC cable are not akin to AC, combined with different operating stresses, it should be expected that DC ages differently. As previously discussed the effect of temperature is essential to the PDIV of DC cables [120] . It should be emphasised that the status of DC monitoring is different from AC, as the technology is in a different phase of its lifecycle. The AC grid is dominated by aged equipment nearing the end of its life expectancy. Furthermore it faces requirements of increased capacity and resilience. Hence there is a large emphasis on the ability to assess and predict cable age and ageing mechanisms in order to maximize effectiveness and ensure stability in the existing grid. Despite a significant population of aged MVDC and HVDC lines and cables, the majority of the installed DC capacity in the near future will be installed within the last decade, thus the ageing problematic will not be as profound. There will be a significant time window to obtain sufficient knowledge on DC cable ageing mechanics. As discussed in chapter 5.4 the current and future integration of HVDC grid will encounter complication with regard to fault protection, system stability and compatibility with existing AC grid, avoiding DC induced destabilization of the AC grid. Hence the current attention is primarily focused on ensuring sufficient technological performance, as the technology still experience performance issues and can not be regarded as a matured technology. The following sub-chapter will assess DC PD detection and DC OHL monitoring.

6.9.1 PD detection

As previously discussed the effect of temperature is essential to the PDIV of DC cables [120]. Initial research found that PD was far less a threat in DC compared to AC[97] [52]. This can be explained by lower PDIV and lower discharge magnitude. PDIV is dependent on the minimum repetition rate. The relation where AC and DC repetition reach equality is given by the following equation:

$$\frac{dV}{dt} = \frac{V}{t}$$

Since the charging time of the cavity t is magnitudes higher than in AC, the repetition rate is significantly lower, thus higher PDIV. When the operating temperature of the cable rises, the conductivity of the cable rises. The repetition rate also increases. Although the same mechanisms are behind PD activity, there have been struggles to directly link the behaviour and characteristics of PD in DC to AC.

For DC PD detection the typical test utilized on AC detection, as described in chapter 6.2.1 , can be applied without problems. Although DC has an absence of phase pulse this can be facilitated by a number of methods. Without the phase pulse, sufficient graphical 3D representation of the PD activity will be absent. With modern AC PD detection methods the characteristics of the present defects can be complexly detailed, as it can be based on discharge magnitude, number of discharges and phase angle, thus providing a 3d plot (φ–q–n). For DC measurements the only parameters available are discharge magnitude and the time between each discharge. To obtain satisfactory characteristics and graphical representation of DC PD a number of methods are recommended:

- PD Magnitude as a function of time: q (t)
- Density function of the PD magnitude: H (q)
- Discharge magnitude and repetition rate as a function of test voltage
- Relation between discharge magnitude and average magnitude of its successor or predecessor
- Relation between discharge magnitude and average time interval
- Cumulative discharge repetition rate as a function of PD magnitude

These are all methods which represent the discharge activity of DC cables as a 2 dimensional plot. Due the various methods available, a complex overview of the PD characteristics can be obtained. For more information on graphical representations of PD activity in DC, see [97].

6.9.2 Online OHL Fault Protection

In HVDC grids even minimal disturbances may cause instability due to fast rise currents due to signal propagating. If not properly isolated and dealt with, these fast rise current may cause harm to the line and cause major instability in the grid. State of art online fault detection can be divided into two main groups [108]: There are non-unit protective and unit protective methods. Non-unit protective fault detection can be defined as techniques that utilize inductors, usually in series, or reactors at the ends of the line in order to facilitate current limitation in the case of fault currents. These are also referred to as single end methods. Unit protective detection methods do not utilize inductors, but rather rely on the communication between both ends of a line to detect faults, and then protect the line by isolating the line.

6.9.2.1 Unit protective methods

For a given plant item the concept of current differential can be utilized. An increase of current over the length of a HVDC line may indicate the presence of fault currents. By employing relays at each end of the line the current on each end of the line can be measured, effectively measuring the current rise across the line. The resulting current differential can then be checked against a predetermined fault threshold, determining if faults may be present. In order to achieve sufficiently fast fault detection, communication between the relays are required. Due to the rapid nature of fault currents the communication link between each relay will need to operate swiftly and without synchronization issues. At shorter distances current differential are a preferred and high performance fault detection method.

At longer distances the performance deteriorates due to time lag, since the communication link now having to travel a significant distance. Studies indicate a cut off length for differential current method performance at 200 km line length [81]. The detrimental effect line length have on time delay may be counteracted by the utilization of additional sensors along the length of the line [133]. A similar method which also utilizes a communication based relay system is the directional protection method. This method bases it fault detection on current direction. If the relays detect a fault current moving in the direction from them, e.g toward the other end, the line gets isolated and will be protected. Due to the dependency on a communication link, this method also struggles with performance on long distance HVDC lines.

6.9.2.2 Non-unit protective methods

When a fault occurs on HVDC line a fault current is generated. Due to the sudden current rise, a resulting voltage drop will ensue. Hence when a fault occurs we operate with two main parameters, overcurrent and overvoltage. Overcurrents are measured at single terminals, utilizing a predetermined threshold to detect whether or not a fault is present. The direction of the fault is determined by the polarization of the current. The major drawback of this method is the inability to discriminate between internal and external fault, e.g if the occurrence stem from the selected line or from elsewhere in the system or external interference. Hence this method is preferably utilized in conjunction with other methods, typically as a back-up measure. The overvoltage detection utilizes the same concept of single terminal measurement, but instead operate with inverse treshold to detect whenever the voltage falls below a certain value. Due to the absence of polarity in the measured voltage, direction can not be determined. These are both considered as attractive methods due to their simplicity and effective measurements.

They are however limited in the information they garner, hence the priority to utilize other methods as the main protection method.

More refined versions of overcurrent and undervoltage methods are current and voltage derivative. These methods utilize high sampling measurements to monitor the change of measured value over a short time duration. If the change of rate exceeds a predetermined treshold, fault is detected. Due to fast sampling rate, the first wave of the fault will be detected, thus the method offers swift fault detection.

Perhaps the most refined and high performance current detection method currently available is the utilization of wavelet transform. Wavelet transform is utilized in a wide range of operations where signal processing is required. The measured signal is processed with advanced software. WT decomposes the measured signal by utilizing mathematical tools such as Fourier analysis and is able to detect small rapid changes and singularities [79] [141]. Due to the fast nature of fault currents, the wave transform is required to process the signal swiftly. There are two main wavelet transforms, Continuous Wavelet Transform (CWT) and Discrete Wavelet Transform (DWT). Of the two, the DWT is the preferred fault detection method due to lower computation time. CWT is more fitted to fault localizing where the computation time is not required to be as rapid. The major drawback of wavelet transform methods is its cost and complexity.

6.10 GIS Monitoring

Although the stability and reliability of GIS installations are high, the potential risk of breakdown have substantial repercussions. The cost of repair is high and requires several days for repairment. If the installation is part of high voltage transmission, e.g high voltage transformer, the repercussion of failure may prove critical to grid capacity and performance. Much progress have been made in the field of GIS diagnostics. The first generations of GIS applications were not fitted with complementary diagnostic systems. Most modern GIS systems are installed with complementary diagnostic systems.

The key parameter to monitor in GIS applications is the presence of particles. Statistics show that the presence of metallic particles is the leading cause to electric breakdown is GIS installations[53][95]. The other main causes of breakdown are protrusions, e.g surface roughness, and non-earthed electrodes [58]. The common denominator of all these causes, is the generation of partial discharges. Common techniques used to detect partial discharges will be discussed. A number of the methods share largely the same concepts as methods previously discussed, hence the technicality of the methods shall not be dwelled on, but rather the effectiveness and applicability of the methods.

We generally divide between two main methods in electrical PD detection in GIS installations. Conventional methods and unconventional methods. The conventional method, or rather the IEC60270 released in 1968 [68], is a widely accepted industry standard due to extensive track record and pass/fail criteria, hence the conventional title. Unconventional methods include UHF method, chemical detection and acoustic detection.

6.10.1 Conventional method

Utilizes coupling devices in a quadripole formation to detect the current pulse propagating from the PD source. The method bases its detection on the concept of lumped capacitance. The pulse which propagates in both directions along the gas chamber have a finite duration, and will die away after approximately a microsecond. The gas chamber can be seen as a lumped capacitor, e.g depleted charge. Ensuing is a replacement charge flowing into the gas chamber. This charge will be measured by a detector. The method is widely regarded as a standard for PD fault detection in GIS installations. It does however have limitations, as it’s unable to locate faults.

6.10.2 Acoustic Detection

The acoustic technique applied on GIS to detect PDs are similar to the technique described in chapter 6.5.

If there is a case of mechanical failure, acoustic detection can also be applied with success. Typical mechanical failure causes are poor connection between switching contacts, loose fasteners and unbalanced shell docking [80]. These poor connections and misalignment, when a electromagnetic force is applied, will induce large vibrations resulting in harmful consequences such as loose bolts, insulator damage and potential SF6 leakage.

PD detection acoustic measuring techniques are able to detect PD sources such as protrusions, floating potential discharges and metallic particles in movement. The acoustic signal does however need to be significantly large in order to be measured with acceptable sensitivity [14]. The method is not suited to function as a permanent monitoring technique due to the requirement of a large number of sensors to obtain sufficient accuracy [58]side 55. For more information on the technicalities of acoustic GIS monitoring consult [91] [69].

6.10.3 Chemical Detection

Utilizes the same concepts as discussed in chapter 6.3. Gas chromatographs and spectometers are utilized to detect the alteration of the chemical composition of the GIS. The gases indicating PD activity are sulphuryl fluoride (SO2F2) and thionyl fluoride (SOF2), which are compounds from sulphur tetrafluoride (SF4). The method is unfortunately deemed too insensitive and is not a viable alternative.

6.10.4 UHF Method

Partial discharges occurring in GIS installations emit electromagnetic waves. The current rise of the discharge is in the nanosecond range, resulting in ultra high frequency waves (UHF), in the range of 300-3000 MHz. The UHF waves will resonate through the GIS chamber, and may be picked up by installed couplers, hence the name UHF method. The method is also referred to as the radio frequency method, or rather RF. Due to the complex design of GIS installations the propagation properties of PD are not straightforward, and sufficient knowledge of the GIS design is required in order to predict the resonance of UHF waves. Although the geometry of GIS installations, such as gas chambers, on paper have straightforward propagating paths, slight details may significantly alter the signal. Discontinuities and non uniformities in the GIS will cause reflections of the signal. Additionally the PD signal consists of several frequency components. The low frequency components will attenuate due to frequency being too low compared to the frequency mode it propagates within.

The placement of the UHF sensors are a delicate matter. The primary objective is obviously to install the sensors in locations strongly predicting the propagation of UHF signals, ensuring high sensitivity and fault localizing. The drawback of installing within the GIS installation, is the fact that the sensors themselves may contribute towards breakdown mechanism. Thus the preferred placement of sensors should be within areas with low HV field [58]. Most modern GIS installations are installed with UHF sensors. For more information on UHF methods see [58][14]

7 Discussion

The subject of this study was to provide a state of the art review of high voltage monitoring, while simultaneously highlighting the role of the electrical grid and its performance in relation to the UN Sustainable Development Goals. The following chapter aims to discuss the information and field literature presented thus far in the thesis. The discussion will be twofold, the first part assessing the environmental and sustainable aspect of high voltage monitoring, while the second part will discuss the state of the art of high voltage monitoring and attempt to indicate future trends.

7.1 UN Sustainability goals

Firstly it should be emphasized that the scope of this paper does not cover the electrical grids role in achieving the SDGs in depth, as the complexity and vastness of this relationship is too substantial. Additionally the majority of the solutions can be contributed to political decisions, which naturally is associated with uncertainty and abstraction. A complete understanding of the relation would require a thorough understanding of the quantifiable impact of energy not supplied, an increase in system reliability and the impact of integrating renewable energy sources. These impacts are all hard to quantifiably gauge. Although exact numbers explaining the relationship may prove difficult to provide, the role the electrical grid have in facilitating the SDGs is unmistakable.

In order to to achieve the goals of the Paris Agreement and the goal of net zero emission by 2050, the only solution will be political unity and a substantial investment in the expansion and resilience of the grid, as the energy sector is the main contributor toward global CO2 emissions (72%). The solution as discussed in this paper can be divided into two. Overhauling the existing aged AC grid, by assessing the overall health of equipment, while simultaneously enhancing the grid resilience and capacity, anticipating the large scale introduction of RES. The second part will be to introduce a large amount of HV grid, predominantly HVDC , in order to facilitate the connection of RES with the existing transmission system. There is no doubt that an improvement in cable ageing monitoring would improve the performance of the transmission system, thus contributing towards the SDGs, however there is no quantifiable way to assess this impact.

The field have displayed an increased interest and effort in preventive maintenance testing in the last decades as revealed by Neetrac. This displays an increased alertness towards the importance of monitoring the ageing process of cables, preferably with frequent regularity, indicating a continuous shift toward a more proactive approach to cable diagnostics, rather than a reactive approach. This will be vital in order to properly assess the grid current capability and resilience.

The focus on cable monitoring in relation to ageing and breakdown did not arise recently. There has been a steady increase in the interest of breakdown mechanisms and the field is in continuous development. The transition from laminated to extruded cables can be credited as the largest technical improvement in cable technology. The improvement can be attributed for increased reliability, better transmission performance and a decrease in environmental hazard compared to its predecessor. Despite initial poor performance of the initial generation of cables, which can be attributed to the absence of jacket, water treeing, and DC induced trapped space charge, the XLPE technology which have out-crystallized as the conventional polymer alternative, now experience excellent performance.

Despite still insufficient knowledge on the ageing mechanism of XLPE cables, especially in regards to PD, studies indicate that the XLPE cable itself is the most reliable part of the a cable system in regard to faults. Failure due to cable insulation is only a fraction of the failure that can be attributed to third party damage and failure in accessories. This poses the question of whether the extensive focus and research on cable insulation should rather be allocated towards the reliability of accessories and third party damage protection measures, where improvement would be more beneficiary to the overall cable system reliability.

Failure mechanisms in accessories are however deeply researched and the field seems alert to the reliability issues related to the operating reliability issues it has. Third party damage is more challenging to gauge, and here we extend the discussion to also involve OHLs. There is a luck factor involved. If we exclude weather induced third party damage, there is high amount of unpredictability and freak accidents involved. Interference such as vehicles and construction work is both hard to predict and prevent against and will unfortunately occasionally occur.

What is certain, however, is a future increase in extreme weather events, which will be the main threat to transmission reliability moving on-wards. Despite the proposed actions towards climate change, the increase in extreme weather will be a dominating factor for the foreseeable future, forcing the field into action. In order to mitigate the repercussions of extreme weather there needs to be implemented resilient protective measures, along with an overall increase in back up grid capacity, so that we avoid catastrophic events such as the Texas Winter Storm of 2021.

The large integration of HVDC in order to facilitate the connection of RES to our energy system is well underway. As discussed in chapter 5.4, China is way ahead of everyone else in regards to HVDC and are venturing in uncharted territory making them technology defining. Due to the rapid development they experience, they can be seen as a template for future challenges, but also for solutions in HVDC technology. At the current stage of HVDC there is limited concerns to the ageing mechanisms of DC lines. The current concerns are rather towards the technical performance of the HVDC, especially in regards to compatibility with the preexisting grid. Especially the performance of CBs and AC/DC converters are of the highest agenda. The challenge of facilitating the integration of RES is then not the ageing mechanisms of the system, but rather its technical performance.

As for the emissions from the transmission system itself, a clear perpetrator in SF6 can be distinguished. Over two decades after the Kyoto Protocol of 1997, where the hazardous nature of SF6 was revealed to the world, there is finally political unity for the reduction of SF6 emissions, as can be seen in the report issued by the European Commission. The delayed response can be partly attributed to an absence of commercially viable gas alternatives. As discussed, studies have revealed, that only a complete transition to SF6 free alternatives will result in a reduction of SF6 emissions long term. As for future trends , utilizing liquid and solid state insulation combined with gas looks to be a viable solution in MV applications, while HV applications will look towards a mixture between highly volatile gases and fluorinated gases. What is certain is that the transition away from SF6 will be a complicated matter as SF6 has been the backbone of gas insulation for over 60 years.

To summarize, the impact high voltage monitoring will have on the achievement of the UN SDGs is hard to quantify. It can however with great certainty be concluded that ensuring high quality monitoring of the future transmission grid will be essential towards achieving a number of the SDGs, be it climate change, equality or innovation.

7.2 State of the art of high voltage monitoring

This paper have in great depth discussed a variety of high voltage monitoring techniques. The main focus have been on the monitoring of extruded cables, however the monitoring of several plant items, accessories and OHLs have also been described.

To obtain sufficient knowledge on the state of the art and future trends of monitoring it is important to assess the development over a significant time period, in order to properly assess the driving mechanisms behind change in the power field. Before delving further into the details, two key observations should be mentioned briefly. The equipment and material utilized in high voltage transmission have changed and will change minimally. There will be improvements in material utilized and the techniques applied, but overall the equipment and concepts will largely remain the same. What is alluded at here is the fact that the knowledge on conventional equipment utilized is under constant improvement, while the premises remain largely unaltered. If we combine this with the drastic advancements of data technology in the last decades, the understanding of key dielectric mechanisms can be accelerated and the statistical basis can be greatly expanded, due to rapid improvements in data processing. This can be regarded as equally important or even more important than the development of new techniques, as the importance of breakdown mechanism knowledge and statistical merit can not be understated.

In regards to cable monitoring two of the formerly conventional methods are falling out of favour and is either strongly advised against or no longer preferred. These are the DC applied testing and simple withstand testing. DC applied testing which once was the conventional method for AC cable testing is now strongly advised against due the repercussion of DC induced trapped space charge. DC applied voltage methods despite their applicability have AC applied voltage tests providing the same function with equal or even better performance.

Simple withstand testing has been a field standard and the most commonly applied method for a long time due to the simplicity of the test and the straightforward pass/fail criteria it offers. As there has been an increased interest and alertness on the presence of defects present in the cable, a simple dielectric withstand assessment of the cable do not longer suffice and the more sophisticated approach in monitored withstand testing is preferred.

The two main conventional methods for specialized cable monitoring test are tan delta and PD measurements. The tests are preferably conducted offline due to the ability to apply voltage exceeding operating conditions. The proposed solution of simultaneous PD and Tan Delta testing have been described. DAC applied testing having displayed great potential as a voltage source as it provides great coverage in defect detection, making it especially attractive in PD detection. However due to standardization issues with other methods the method have struggled to gain utility.

While DAC struggles to gain utilization, VLF methods are a dominating force. The method provides overall great performance, eliminates the requirement of a large power source resulting in a simplified set up. Additionally it has few disadvantages. Based on the research conducted in this study, it has not been found any evidence indicating that VLF will not be the dominating voltage method in the foreseeable future.

Dielectric spectroscopy is the main ”challenger” to Tan Delta and PD. It offers a depth in extracted information which in certain aspects exceeds that of the other methods. It does however have major drawbacks, mainly in complexity and required test duration. The possibility of trapped space charge should also cause concern. Hence Dielectric

Spectroscopy is still only regarded as a niche method, experiencing a limited amount of utilization. However if kept in mind the rapid growth Dielectric Spectroscopy has experience in the recent decade in a wide range of fields, combined with the possibility of a non-invasive approach, it should not be disregarded as a potential conventional diagnostic method within the foreseeable future.

While mentioning non-invasive methods, it should be noted that currently there are no non-invasive method displaying sufficient performance when applied to cables too justify conventional utilization in maintenance testing. The two main classical non-invasive methods thermography and acoustic detection both have their utility in the monitoring of various high voltage equipment, but in relation to cables their utilization is severely limited. Although acoustic monitoring is the main preferred method in the pin-point phase of fault locating, its utilization seems to limited to only this application.

In the field of fault locating TDR holds firm as the major conventional method, and there a few indications that this will change. The largest advancements within the field of fault locating will be in subsea cables, as the current knowledge and techniques do not match the increased importance these installations provides. Although not deeply discussed in this thesis, the development of subsea monitoring should be of the utmost interest as it has potential for large innovations in monitoring techniques.

8 Conclusion

This thesis has provided a State of the Art review of high voltage monitoring while also focusing on the role high voltage monitoring has in relation to the UN Sustainable Development Goals. The study have primarily focused on the monitoring of high voltage extruded cables, but have also provided an extensive overview of the majority of high voltage installations

Although no quantifiable relation between high voltage monitoring and the SDGs can be presented, this thesis have showed that the role and performance of high voltage monitoring is an important factor if the UN are to achieve their current goals. The field of high voltage monitoring is required to emulate the rapid pace of energy demand and integration of new technologies. If the monitoring and dielectric assessment of the current and future grid is insufficient, the integration of renewable energy, which is the key to achieving the SDGs, will be hampered and prove challenging. The thesis has emphasised the importance of proper assessment of the existing grid in order to analyze its challenges, capabilities and rooms of improvement, all in order to properly facilitate the integration of renewable energy and HVDC technology. Another key aspect that been described is the increase in extreme weather events and how it will greatly harm the integrity and stability of the transmission system, potentially greatly exceeding the improvements made in insulation monitoring.

The field of high voltage have displayed a continuous increase in the interest of cable ageing, especially on partial discharge mechanics, indicating a surge in proactive approach by the field. A broad selection of relevant monitoring techniques have been presented. Currently the main conventional maintenance methods are VLF Tan Delta and VLF PD measurements, while TDR holds firm as the conventional fault locating method. Niche options which display great potential such as DAC and Dieletric Spectroscopy have also been discussed.

The key environmental concern of the transmission system have been identified as SF6 gas, the most potent greenhouse gas known. There is currently large resources allocated to developing alternative solution with suitable properties, as only a complete out phasing of SF6 will lead to reduction in emissions.

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