CZECH TECHNICAL UNIVERSITY IN PRAGUE

Faculty of Electrical Engineering

Department of Electrical Power Engineering

Cable systems for HVDC Power Transmission

B a c h e l o r   T h e s i s

Study program: Electrical Engineering and Computer Science

Field of study: Power Engineering

Supervisor: doc. Ing. Radek Procházka, Ph.D.

Duan Chengyan

Prague 2018

BACHELOR'S THESIS ASSIGNMENT

I. Personal and study details

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Study program: **Electrical Engineering and Computer Science**

II. Bachelor's thesis details

Bachelor's thesis title in English:

Cable systems for HVDC Power Transmission

Bachelor's thesis title in Czech:

Kabelové systémy pro vysokonapěťový stejnosměrný přenos

Guidelines:

- Overview of power systems for HVDC transmission
- Cable construction and used insulation materials for HVDC applications, description of main characteristics and parameters
- Experimental comparison of voltage-time characteristics on XLPE samples stressed by DC and AC voltages

Bibliography / sources:

[1] Kuchler, A.: High Voltage Engineering Fundamentals-Technology-Applications, Springer 2017
[2] Malik, N., H., Al-Arainy, A., A., Qureshi M., I.: Electrical Insulation in Power Systems, Marcel Dekker Inc., 1997

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Date of bachelor's thesis assignment: **16.02.2018** Deadline for bachelor thesis submission: **25.05.2018**

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III. Assignment receipt

The student acknowledges that the bachelor's thesis is an individual work. The student must produce his thesis without the assistance of others, with the exception of provided consultations. Within the bachelor's thesis, the author must state the names of consultants and include a list of references.

Date of assignment receipt

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Declaration

I hereby declare that this thesis is the result of my own work and all the sources I used in the list of references, in accordance with the Methodological Instructions of Ethical Principle in the preparation of University thesis.

In Prague 22.05.2018 C. Duan signature: …………

Ackonwledgement

I would like to thank especially the doc. Ing. Radka Procházka, Ph.D., for advice and comments during writing. I would also like to thank Ing. Ondřej ŠEFL, for all the help with the experimental part of the work. I must also not forget my family, who supported me as much as possible throughout my whole studies.

Poděkování

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Title: Cable systems for HVDC Power Transmission
Author: Duan Chengyan
Field of study: Power Engineering
Type of thesis: Bachelor thesis
Supervisor: doc. Ing. Radek Procházka, Ph.D.

Abstract: This thesis investigates the HVDC cable transmission systems. An experiment is conducted where AC or DC voltage is applied to XLPE samples. Dielectric strength and time to failure of various voltage levels are recorded. Ultimately, the performance of XLPE insulation on the HVDC power transmission cable is discussed.

Keywords: HVDC power transmission, HVDC cable insulation, XLPE

Název práce: Kabelové systémy pro vysokonapěťový stejnosměrný přenos
Autor: Duan Chengyan
Obor: Energetika
Druh práce: Bachelor práce
Vedoucí práce: doc. Ing. Radek Procházka, Ph.D.

Abstrakt: Tato práce zkoumá kabelové přenosové systémy HVDC. Pokus se provádí tam, kde se na XLPE vzorky aplikuje střídavé nebo stejnosměrné napětí. Dielektrická pevnost a doba do selhání různých úrovní napětí jsou zaznamenávány. Nakonec se zabývá výkon izolace XLPE na kabelu přenosu energie HVDC.

Klíčová slova: HVDC přenos síly, izolace kabelu HVDC, XLPE

Table of contents

Introduction

Power transmission has always been an essential part of the electric system. Its presence ensures that the electrical power generated by the power generation site such as power plant, can be transmitted to the distribution system.

The quality of power transmission system is proportional to the amount of power need to be supplied, the amount of power losses during the transmission, the probability and risk of a failure and so on. For technical and economic purposes, these parameters are very important and the insulation quality of the power transmission system stands for a huge influence.

Since the transmission system is getting more complex today and the request of reliability for the transmission system is getting higher and higher. And the flexibility, transmission security and expansion ability of the transmission system are also gradually gaining attention. The HVAC transmission system which is the main part of transmission system today is facing big problem to achieve these requirements, not only the technique issue but also economical issue. For instance, the mutual inductance and capacitance, the synchronization of the grid and the high reactive power losses.

Because all of those factors, people are pushed and encouraged to find another way of development, both technical and economical. An earlier technology was re-attention by people which are DC transmission.

The first well-known DC transmission system in 1954 is cable transmission and the cable transmission is the main part of HVDC transmission method nowadays. For this reason, many researchers focused on insulation of HVDC cable transmission system and a lot of works were published over the years.

This thesis gives a brief review of HVDC transmission system of its history, the advantage of HVDC transmission system compared to the HVAC transmission system, or the motivation of using HVDC transmission system, the component and the structure of HVDC system.

The second part described the insulation of HVDC transmission using cables. The construction of various cables and the problem and issues met. Although only the problem related to the XLPE insulation is showed since it is one of the most focused material in the area of insulation used for HVDC power transmission system.

The third part is the practical part which involved an experiment to make the comparison of XLPE under AC and DC voltage, the difference of dielectric strength of XLPE and the difference of voltage-time characteristic under AC and DC voltage. The setup of the experiment, the result and conclusion form the last part of this project.

1 HVDC transmission system

HVDC transmission system is an electrical transmission system that uses direct current rather than alternating current. The main task of such system today is to construct a "reliable, efficient, sufficient, flexible and clean" power grid. When installed, the HVDC transmission systems often form the backbone of the grid.

1.1. History and development

In 1901, Hewitt's mercury-vapour rectifier was present which gives the transmission of DC power at high voltage levels and long distances a chance to make it possible. In 1930, the improved version of the mercury arc valves was developed and in 1945 a commercial HVDC system in Berlin was commissioned but never gets a chance to operate. In 1954 Sweden constructs the first HVDC power transmission line connecting its mainland and island of Gotland with 96km submarine cable, 20MW and 100kV. Volgograd-Donbass project in 1962 was the first overhead HVDC transmission line in operation with 470km, 720MW and±400kV. In 1967, Sardinia – Italy HVDC system uses sea and ground to complete the loop with 121km, 200MW and±200kV. What's more, in 1987, after upgrade, it is also the first HVDC transmission system that has more than 2 terminals and the power increased to 300MW. In 1970, US construct an HVDC transmission line connecting two AC transmission line with 1372km, ±400kV and 1440MW.

In 1972, Eel River DC power transmission project with 320MW, first applied SCR valve thanks to the development of power electronics and semiconductors. From that time, nearly all new DC power transmission project uses the thyristor-based valve in ultra-high voltage. Also, the power transmission ability has grown sharply and such thyristor-based line commutated current source converter (CSC) technology is used in the majority of HVDC transmission. The Three Gorges – Shanghai link is one of the largest with a rating of 3000MW and ±500kV.

Now, the HVDC transmission systems were put into use all around the world and dozens of new HVDC transmission project are underway. It greatly proves the using of HVDC transmission has a lot of benefit from now to the future.

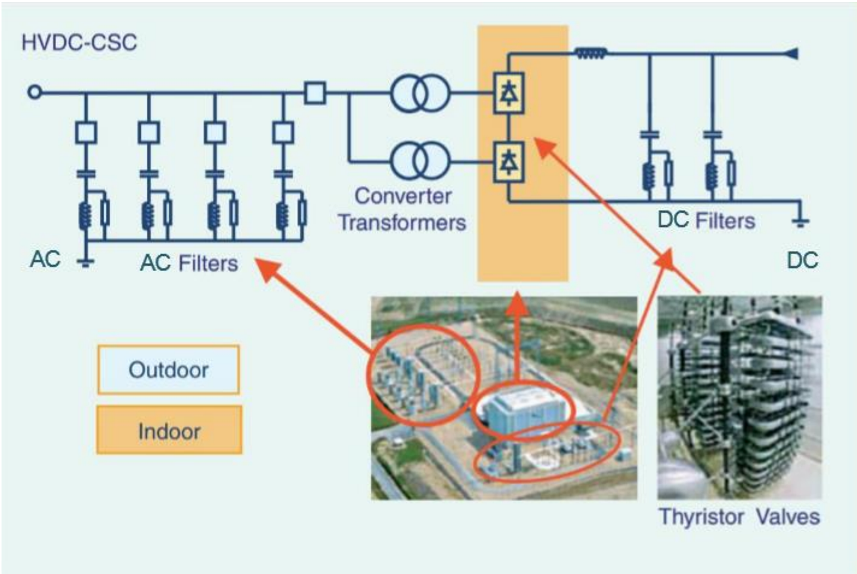

Figure 1 Conventional HVDC with current source converters [11]

In 1999, the first commercial VSC based HVDC, or VSC-HVDC transmission was first commissioned on island of Gotland with 50MW [1].

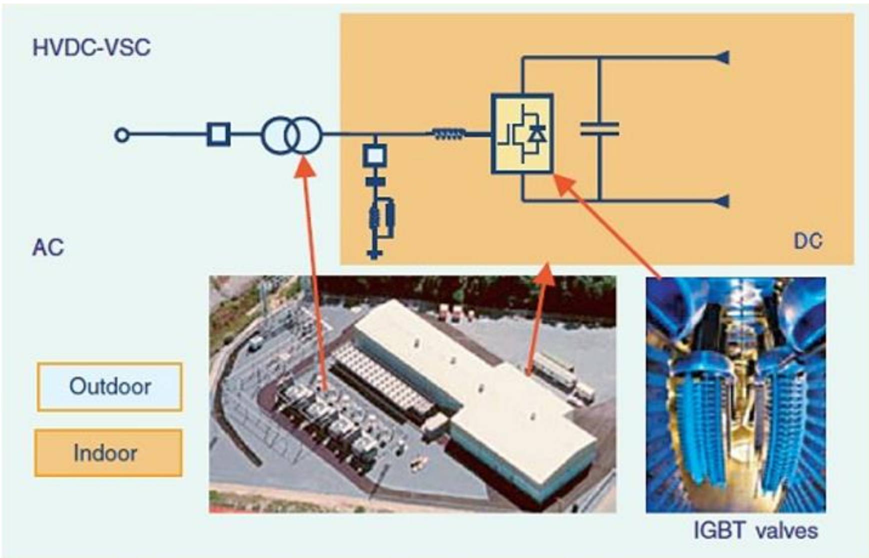

Figure 2 HVDC with voltage source converters [11]

Now, it is not a secret that technology is greatly rising every day including HVDC power grid. The main development stimulating factors are

Globe warming

Climate Change

Significantly soar of energy consumption

The desire of using nuclear and renewable energy

Ultra-long distance power transmission is a trend

1.2. Motivation of using HVDC transmission system

The dramatic rise in power demand and rapid expanding of human activity in recent years accelerate the need of long-distance power transmission and trade of power between different AC systems, and integration of renewable energy. These result in an increasing interest of research in HVDC transmission. It is currently seen as a viable option as a supplement for AC technology and the trend of development for power transmission. In general, the HVDC could be a very effective tool to build a perfect power grid, to achieve both technological and economical goal for the sustainable development of human society and to improve the ecological situation on earth.

1.2.1. Technological

At the technological point of view, HVDC power flow is totally controllable, fast and accurate. It also can enhance the stability of power grid. By linking two synchronous AC systems using HVDC technology, it can improve the controllability of power flow from one to another to prevent large cascading failures or even a blackout in the power grid so the stability of whole grid can be better. Then, the HVDC technology can connect two asynchronous power systems even at a different frequency. This interconnection acts as a buffer in case of cascading failures or disturbances in one of those systems which are very beneficial. It is worth mentioning that there is no stability limit related to the amount of power or the distance of transmission for HVDC interconnection. What’s more, there is no limit to the length of a HVDC submarine cable.

1.2.2. Economical

For the economical point of view, the HVDC technology can save a huge amount of cost for long cable transmissions and long distance bulk power transmissions. Since for DC, the frequency is zero, the inductance is irrelevant, so there will be no induced losses in conductor, sheath, armoring, neighboring cables, and no need of compensating inductance along the transmission line. So there will be lower energy losses in long-distance power transmission which means lower cost at the power losses. Then, HVDC is also irrelevant with capacitances so there are no losses in reactive power compensation equipment along the transmission lines. It is worth mentioning that undersea transmission line is possible thanks to this characteristic. Apart from that, in poor weather conditions, the corona losses of HVDC transmission line are less than AC and the radio interference results from corona discharges from a DC line is lower than an AC line in a similar capacity. Last but not least, HVDC transmission needs significantly fewer lines than HVAC. What's more, in some design of HVDC transmission it only needs one signal line.

1.2.3. Ecological

Finally, from the ecological point of view, the HVDC transmission has a low impact on the surrounding environment. Firstly, HVDC transmission requires less space than AC since the size of the tower for HVDC is lower when compared to the tower of HVAC systems and the right-of-way width for DC line is reduced too. This is just for overhead line solution. If an underground cable is used, the only thing needs large space is converter stations. Apart from that, HVDC produces a stationary magnetic field which affects less on the human body than HVAC. Last, there is no evidence of generation and emission hazard from any operating DC line.

1.3. Basic complements

1.3.1. AC Breaker

AC breakers are used in the case when the HVDC system is malfunctioning so AC system can be isolated from HVDC system.

1.3.2. AC Filters

AC filters are used to remove current and voltage harmonics which could overheat the generator or disturb the communication system.

1.3.3. Capacitor Bank

Capacitor banks are used to provide reactive power to convert AC power to DC or vise-versa.

1.3.4. Converter Transformer

Converter transformers are used to transform the voltage from AC side to DC and separate these two systems. They can provide the right value of voltage required at every load points, compensate the internal voltage drops of the HVDC converters, compensate for the deviations in the AC bus bars from correct value and limiting the short-circuit current.

1.3.5. Thyristor Converter

Thyristor converters are the vital part of HVDC transmission system to convert AC to DC or vise-versa.

1.3.6. DC Filters and Smoothing Reactors

DC filters and smoothing reactors together can protect the converter valve in case of failure of commutation.

1.3.7. Auxiliary systems

Auxiliary systems of HVDC including cooling systems, control systems, and power supply back-up. The valve cooling systems are significantly vital since an outage may result in huge damage to the valve.

1.4. Basic System of HVDC

1.4.1. Point to Point system

Point to point system is the category of most HVDC systems. It can be contrasted in cables, overhead lines, and a combination of them. Two basic point to point system is shown in figure 3 and figure 4.

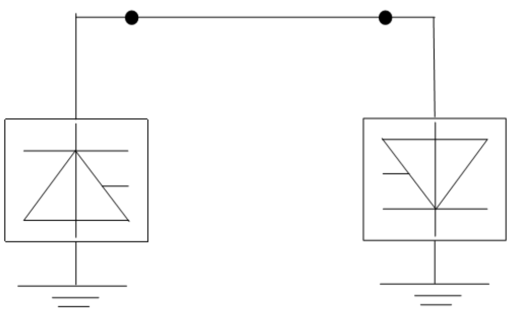

Figure 3 Monopolar system

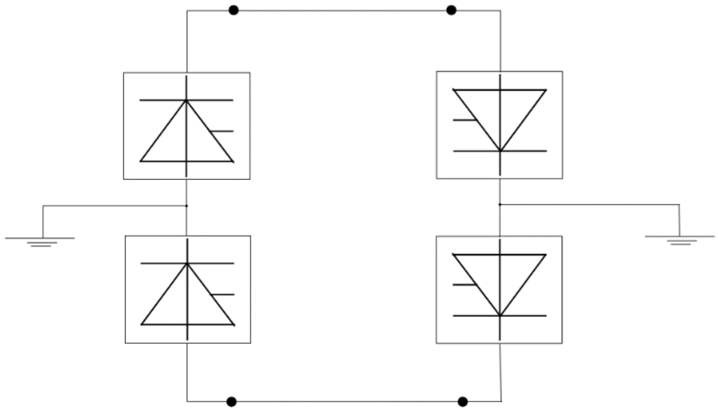

Figure 4 Bipolar system

1.4.2. Monopolar HVDC

A monopolar HVDC make up of a single conductor and a return path through ground or sea. It is mainly used for transmission of power using cables and whether to use or

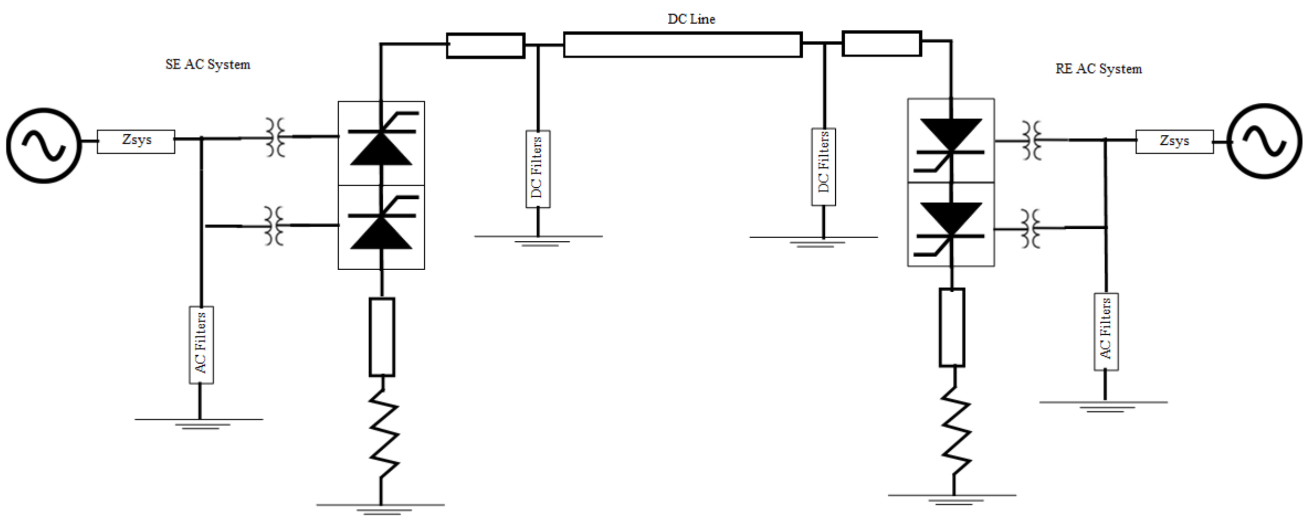

Figure 5 Monopolar HVDC system

not using this system is dictated by the cost of cable installation. The construction of a monopolar system is shown in figure 5.

1.4.3. Bipolar HVDC

A bipolar HVDC consists of a pole with positive polarity and a pole with negative polarity. The amount of power transmitted by bipole is two times larger than monopolar one, it also creates fewer harmonics than the monopolar case. What's more, it is possible to reverse the power flow just by converting the polarities of two poles. Finally, if one of the poles malfunctions, the other pole is still able to transmit the power with a ground return, this shows the two poles of bipolar HVDC can operate separately as well. It is also worth mentioning that in steady state, no current is flowing through the ground return which also means the current flowing in two poles is the same. The construction of a bipolar system is shown in figure 6.

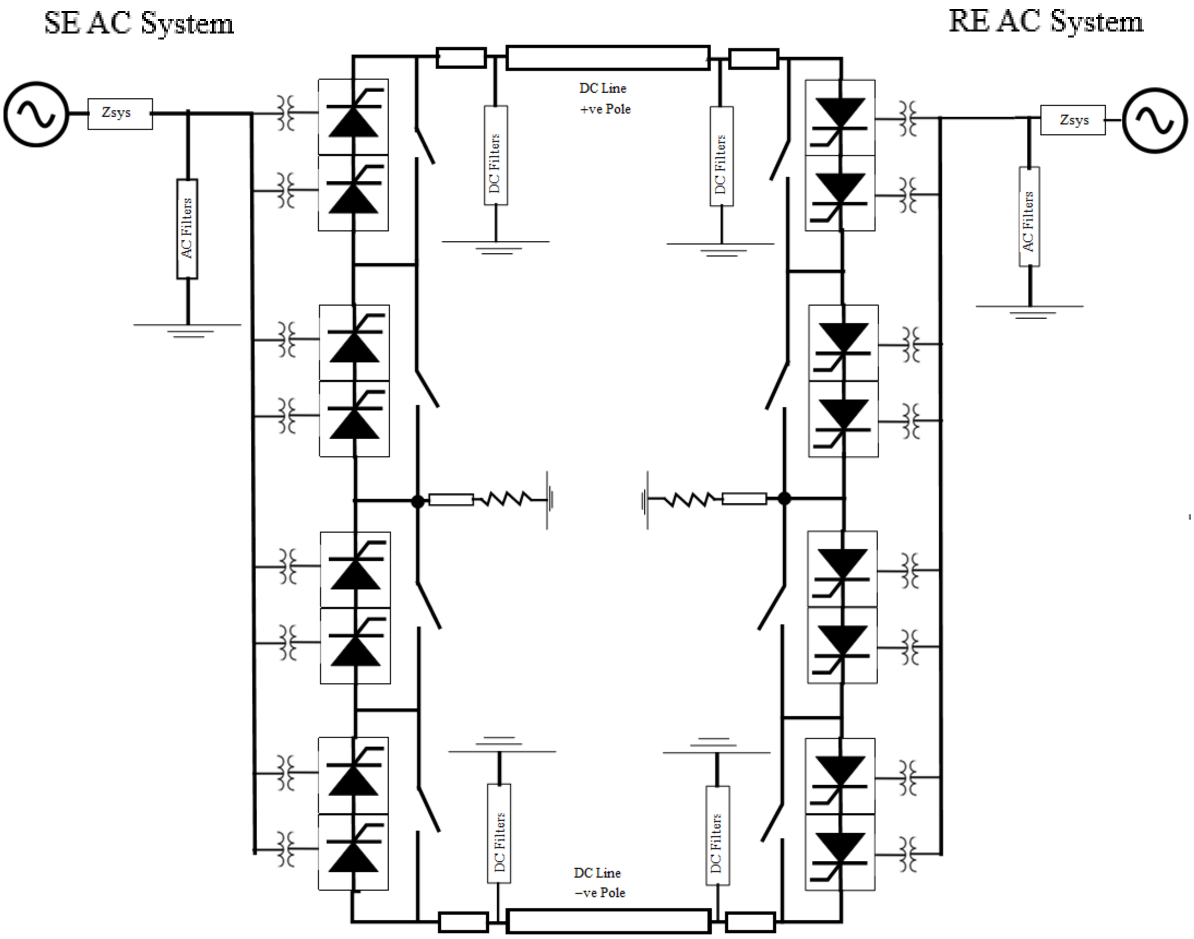

Figure 6 Bipolar HVDC system

1.4.4. Back-to-Back system

Back-to-Back system is usually installed for two different AC systems to have an asynchronous interconnection. The rectifier and inverter are at the same station in this case.

1.4.5. HVDC Multi-Terminal

The HVDC Multi-terminal is more complex than point to point HVDC systems since it consists of more than two transforming stations and it requires a dramatical complexity to boost control and communication between each of these stations. But HVDC Multi-Terminal technology has huge potential for various applications in different areas in the future. Two types of HVDC multi-terminal system which is parallel multi-terminal and serial multi-terminal is shown in figure 7 and figure 8.

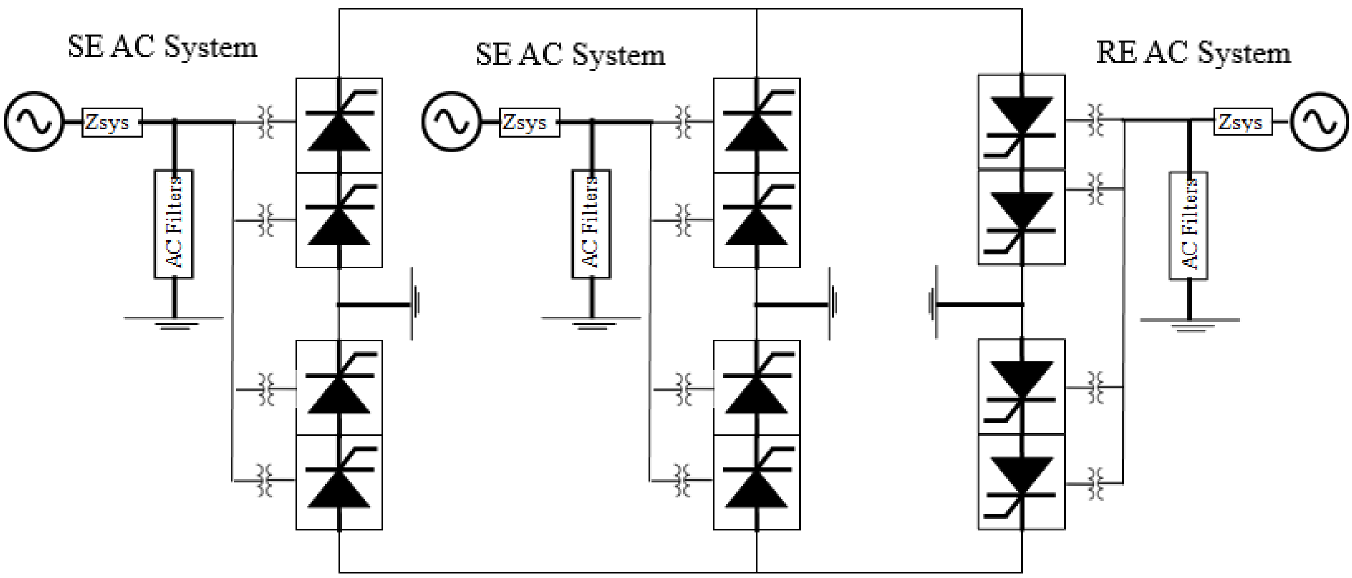

Figure 7 Parallel Multi-Terminal link

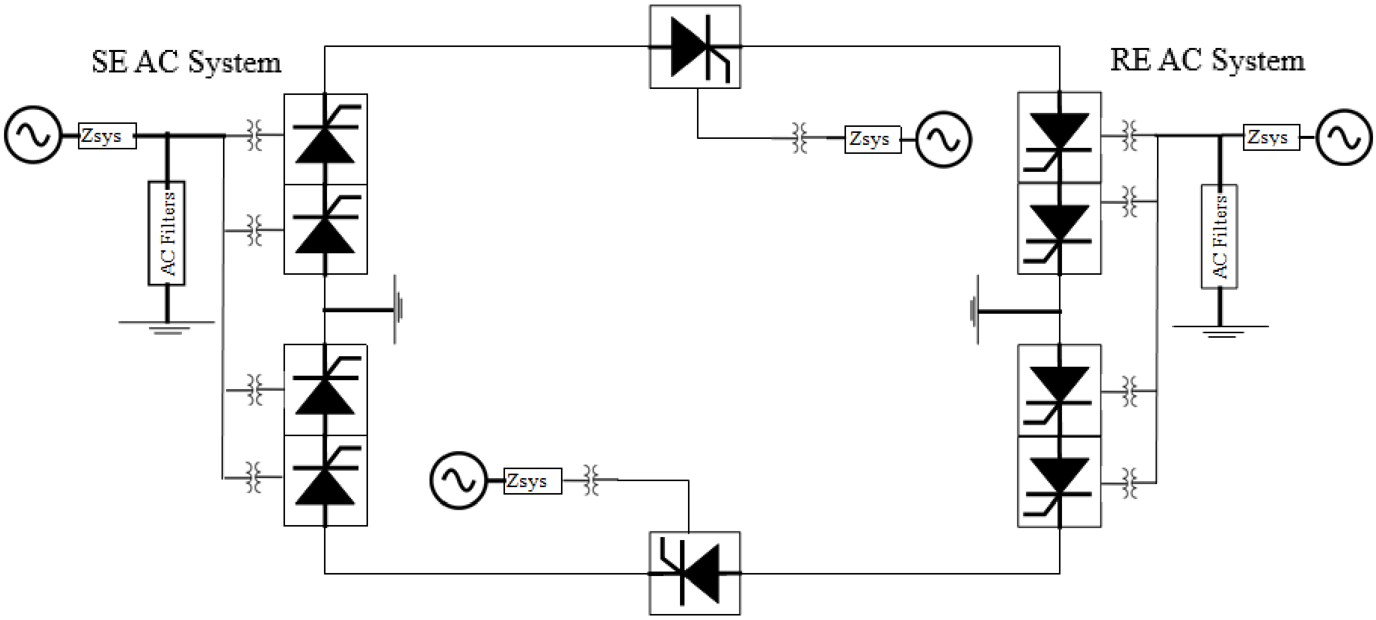

Figure 8 Serial Multi-Terminal link

1.5. Transmission construction

1.5.1. Overhead lines

(1) Bipolar Line

Almost all HVDC systems with overhead lines are bipolar systems. The essential factor is required minimum clearance. Two type of construction of the overhead line tower is shown in figure 9 and figure 10.

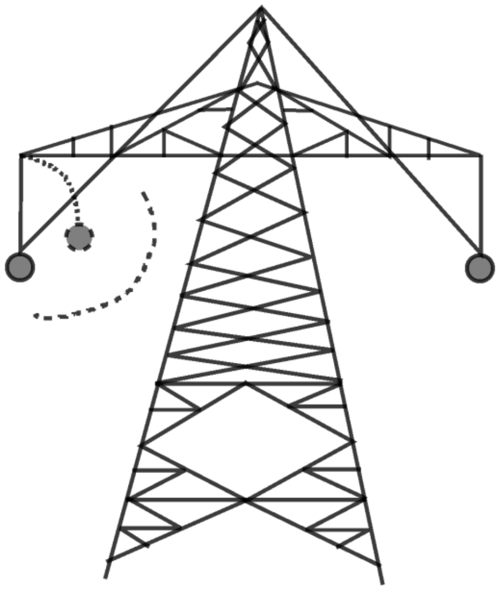

Figure 9 Bipolar HVDC line

In the type of construction shown in figure 9, the swing width can be reduced so the cross arm can be shorter. If the ground resistance is too high in the runs though region, the tower can connect one by one using the non-insulated cable, such action not only lower the footing resistance, but also prevent flashovers caused by lightning strike.

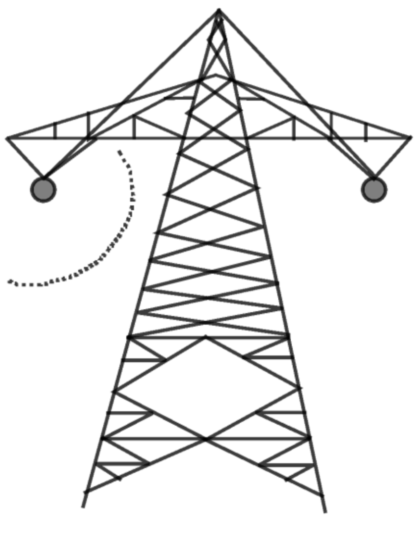

Figure 10 Bipolar HVDC line with V-strings

In the type of construction shown in figure 10, the conductor is held on V-strings, the required width can be reduced but the clearance is reduced and this will cause some negative effect.

(2) Double Bipole line

A double line system can avoid an outage of the HVDC system when the tower collapses.

(3) Line with Neutral Bus Conductor

A line with neutral bus conductor can still transmit ~50% of its nominal power even one pole is malfunctioned. The neutral bus also can be used as the overhead ground wire to reduce the cost.

1.5.2. Cable

There is nearly no difference for construction of an HVDC cable compare to the construction of a single-core HVAC cable. But it is worth mentioning that some of the phenomena that are vital in HVAC cable systems can be neglected in HVDC systems, and vice-versa.

The capacitance in HAVC cables will result in a charging current that will eventually reach the level of the nominal current and such phenomena do not occur in HVDC cables.

The skin effect is also a phenomenon that only important in HVAC cables. In HVDC case is an increased damping.

The constant changing in polarization only occurs in HVAC cable, this will cause dielectric losses and aging of the insulating material.

Eddy current losses in the cable are the problem only happened in HVAC cables. For HVDC cables such phenomena can be ignored.

The insulation material of HVDC cable has a strong temperature dependence of the specific resistance which limits the design of the cable and affects heavily of its operational behavior.

In general, the technical characteristic for HVDC cable shows a lot of advantages that around three times the power can be transmitted per cable conductor with the same cost for material compared to HVAC cables [2].

2. Cables

2.1. Type of cables

2.1.1. Paper-Insulated Mass-Impregnated Cable

Paper-Insulated Mass-Impregnated Cable is the most widely used type of cable in HVDC systems. It is built up with multiple layers of special paper (mostly Kraft paper) and this paper is impregnated with viscous insulation compound. In theory, such cable does not have length limit and has good performance when using as submarine cable.

2.1.2. Gas-Insulated Internal-Pressure Cable

This type of cable using insulating gas (mostly nitrogen) that introduced through a hollow passage inside the conductor under a specific pressure. It is often believed that pressurized gas against the external water pressure on undersea cable and the transmission length has no limitation with the increase of electric strength. And there is another type of gas insulated line system shown in Figure 11. The conductor of such system has a large cross-sectional area. It is used to ensure high power ratings and low losses.

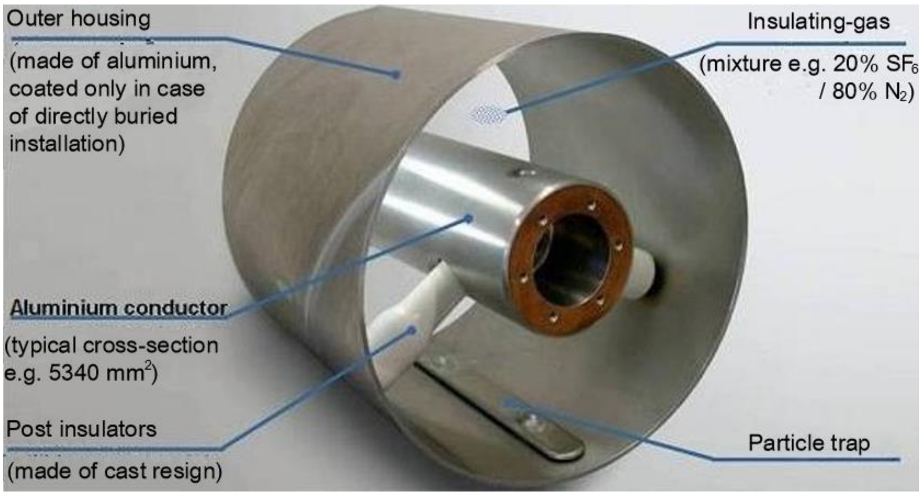

Figure 11 Gas insulted line used for HVDC systems [35]

2.1.3. Oil-Filled Cable

Oil-filled cables are also known as fluid-filled cable. This type of cable is usually filled with pressure oil in the oil channels and using multiple layers of impregnated Kraft papers as main insulation. Two different types of oil are used. First is low viscosity oil. Such pressurized low-viscosity insulation oil can greatly improve the performance of paper insulation. It can both enhance the heat dissipation and decrease the insulation thickness at a specific voltage level. But it requires pressure feeding units and refill tanks to maintain the high pressure in the cable to avoid bubbles. As a result, to keep sufficient oil flow in the cable, the maximum length of cable is just 30-60km. [12,13]. Another type is using high viscosity oil. This type of cable can maintain a flat pressure along the cable and it is so called self-contained oil-filled cable. The advantage of this type of cable is no oil feeding units are needed and the length of cable is unlimited in theory [12,14,15]. A sample construction of the oil-filled cable is shown in figure 12.

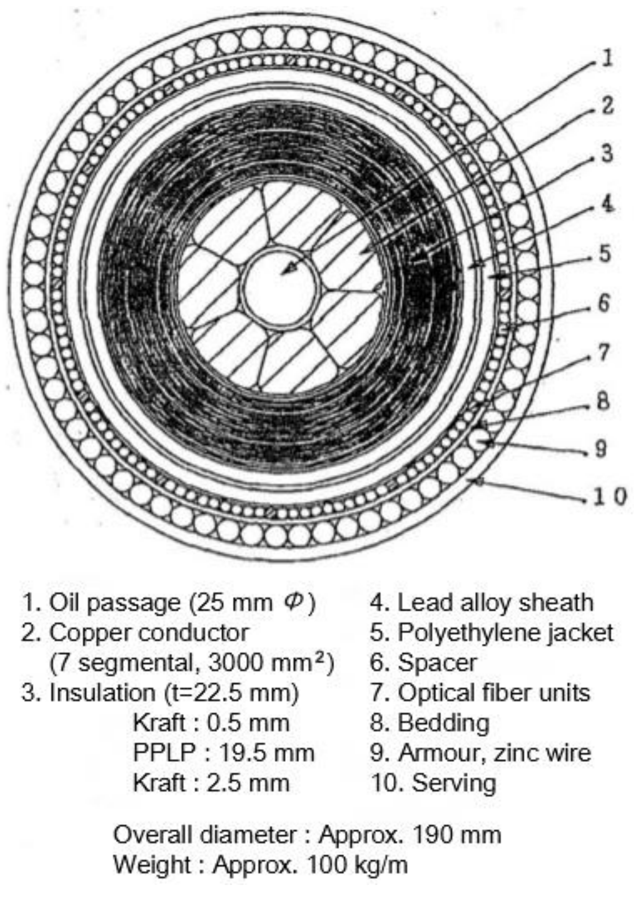

Figure 12 Construction of 500kV DC PPLP oil-filled cable [16]

2.1.4. Extruded Cable

Extruded cables use an extruded polymeric material as the insulation which is the relatively new technology for DC cables. It has the advantage of low cost, high reliability, good electrical properties and good mechanical properties.

Some advantages of extruded cable compared to paper insulated cable [2,13,17,18,19].

Can withstand a higher temperature

Able to use lighter moisture barriers to decrease the weight

The installation is simpler, means less skill is needed

Lower environmental damage in long-term (oil leakage)

This type of cable insulation was very successfully used for underground transmission and distribution of power in HAVC. But for HVDC installations there are some problems, especially space-charge problems in the dielectric led to field strength distribution which will finally cause local increases in field strength and breakdowns. The majority of insulation polymeric material for extruded cable is cross-linked polyethylene (XLPE) [2,19]. But the production of XLPE cable has a disadvantage of high cost and low efficiency. Then, it is hard to recycle the insulation waste and incineration disposal of XLPE not only pollute the environment but also waste the resources.

It was found out that nanoparticles show a great ability to enhance the performance of the polymeric materials. Since the particle sizes, shapes, and doping levels of nanoparticles are different, the polymer matrix that composes nanocomposite dielectrics is also different. It shows not exactly the same effect on improving the dielectric properties such as suppresses space charge, resists electric treeing and increase the breakdown strength, thermal properties such as thermal conductivity and heat resistance. As well as improving mechanical properties such as tensile strength.

Extruded cables that use XLPE material show a great performance even at UHVDC power transmission systems. The main drawback of extruded XLPE cable is the impact caused by space charge.

2.2. Space Charge

The behavior of space charge in XPLE material has attracted a lot of attention. Space charge distorts the electrical field in the diode and affects the following steady-state current. Under high-voltage stress, the generation and accumulation of space charges in the dielectrics alter the electric field distribution, it also accumulates in solid dielectric and the electric field distribution will be distorted, if the space charge density is too high, the local field strength may surpass the breakdown strength of the dielectric and finally lead to a dielectric failure. It also accelerates the aging and degradation of the cable [19,21].

2.2.1. Origins of space charge

The accumulation of space charge within polymeric insulation material is a very complicated process. It not only affected by the charge injection, transportation, extraction, trapping and de-trapping process, but also depends on the electric field, temperature, thickness of the insulation and other factors [25,30].

It is often deemed that charge injection from the electrodes is the origin of the homocharge near the electrodes [31,32]. This homocharge injection and accumulation would decrease the electric field near the injection electrode and increase the electric field near the opposite electrode. Then, the impurities are often introduced into the insulation by the cable production process and the cross-linking byproduct of XLPE act as impurities as well. Such impurities under DC electric field would thermally ionize into ions which are positive and electrons that are negative [33]. Some of those ions and electrons which are not recombined would migrate to the anode and cathode, respectively. At last, they may be trapped by the charge traps near those electrodes which form heterocharges [34].

The space charge density ρ in steady DC current field with the current density j can be given as:

$$\rho = j\nabla\left(\frac{\varepsilon_r\varepsilon_0}{\sigma}\right) \tag{1}$$

where ε_0 is the permittivity of free space, ε_r is the relative permittivity of the insulation material and σ is the conductivity of the insulation material. For polymeric insulation materials, the conductivity depends on temperature and electric field hugely, so the corresponding variation of permittivity is much smaller so the charge density expressed in equation (1) does not equal to 0 [25].

2.2.2. Behavior of space charge

The thickness, temperature and electric field affect the behavior of the space charge greatly. In the different thickness of the XLPE insulation, the space charge distributions under room temperature have strong equivalence in the peak value of the charge density. At higher temperature, the thermal dissociation is promoted, and the thicker is the insulation, the higher probability of trapping or recombining of charges. The increase of the thickness increases the charge mobility at the initial depolarization stage and shallows the trap depth, the shallower traps is, the easier for a charge to de-trap and transport. Two kinds of traps are in polymeric materials: physical traps and chemical traps related to the physical and chemical defects, respectively. It is worth mentioning that most of the physical traps depth is less than 0.3 eV [22]. So, it is clear that the chemical traps are greater involved, the presence of carbon-carbon double bonds in XLPE cause less stability in the presence of thermal gradient [24]. With a higher temperature, the heat dissociation of impurities causes lower trap depth in thicker dielectrics and introduce new low-energy level trap bands. Last but not least, the electric field can increase the energy of charge carriers so it can be easier for those charge carriers to exceed the barriers, and the space charge from thermal ionization would increase with the applied electric field. What's more, the increase of the thickness also increases the impurities [21]. The cross-linking byproducts act as impurities in XLPE material. To reduce the accumulation of space charge and improve the maximum field enhancement, material treatment processes of XLPE such as degassing is needed [23].

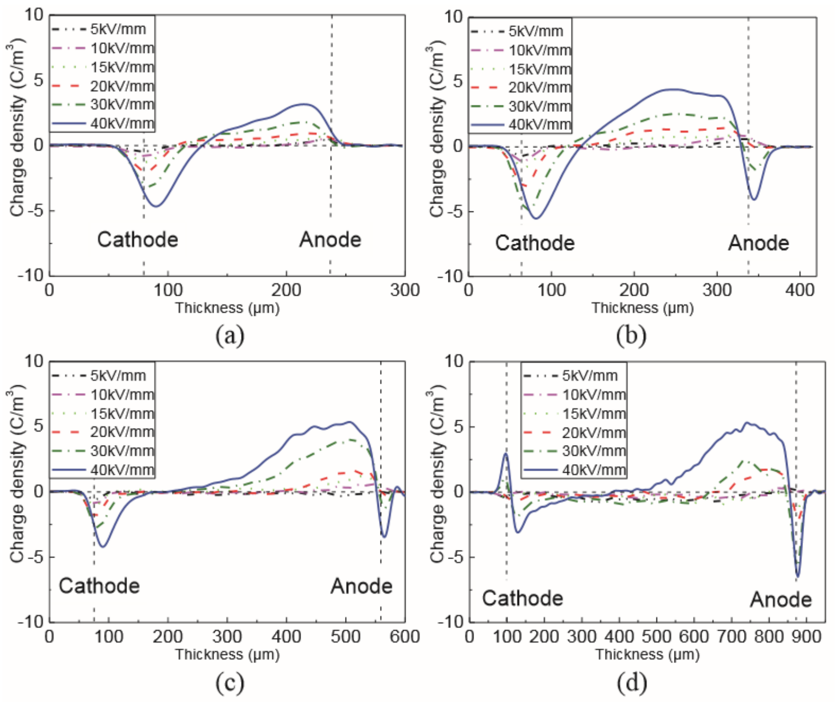

Figure 13 Space charge distribution of XLPE samples at room temperature: (a) 150 μm, (b) 300 μm, (c) 500 μm, (d) 800 μm [21]

2.3. Field strength distribution in the HVDC cable

The electric field distribution in DC cables depends on the distribution of volume resistivity and the magnitude orders of DC volume resistivity for polymeric materials is changes by 2 to 3 in the range of temperature from 20 °C to 90 °C [25]. Because the resistivity is temperature dependent, so the electric field distribution is also dependent on temperature, or the electric field distribution changes with load current in DC cable. And the voltage drop in DC across the insulation of the HVDC cable is determined by insulation conductivity of the material [2]. The dependence of volume resistivity ρ on electric field E and temperature T follows the relation of the form [26]:

$$\rho = \rho_0 \exp(-\alpha T - \beta E) \tag{2}$$

where ρ_0 is the resistivity of the reference temperature, α and β is the coefficient of temperature and electric field, respectively. The electric field distribution E(r) at radius r in DC cables can be calculated as [27,28]:

$$E(r) = \frac{\delta U_0 \left(\frac{r}{r_0}\right)^{\delta - 1}}{r_0\left(1 - \left(\frac{r_i}{r_0}\right)^{\delta}\right)} \tag{3}$$

$$\delta = \frac{\alpha \frac{W_c}{2\pi\lambda} + \beta \frac{U_0}{r_0 - r_i}}{1 + \beta \frac{U_0}{r_0 - r_i}} \tag{4}$$

where λ is the thermal conductivity of the insulation material, r_0 and r_i is the outer and inner radius of the insulation, respectively. U_0 is the voltage across the insulation and $W_c = I^2R$ which is the Joule loss of the conductor.

2.4. Electric field inversion

The electric field distribution in DC cables depends on the load current. Because volume resistivity, in the case that the cable is under DC voltage but no load current, the distribution of electric field in DC cables is different from AC cables and the highest electric field appears at the inner part of conductor in this condition. For loaded DC cables, the strongest electric field may appear at the outer insulation shield and this is so called field inversion. Figure 14 shows the electric field distribution in various dielectric materials and it is clear to see the field inversion phenomena.

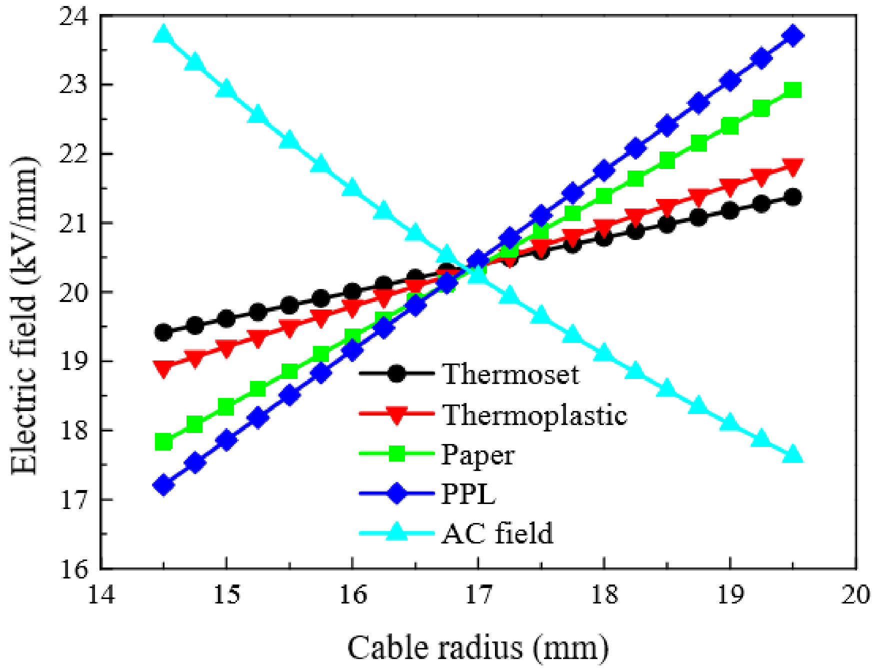

Figure 14 The electric field distribution in 100 kV DC cables with different insulations material under operation. The power loss Wc keeps the same [29]

It is worth mentioning that the field inversion which depends on load current and the lack of theoretical dependence of DC volume resistivity on temperature and electric field make the design of insulation for HVDC cables very difficult.

From equation (4), we can see, to reduce the impact of electric field inversion, higher thermal conductivity would be very helpful to reduce the temperature gradient through the insulation material and suppress the electric field inversion. What's more, the temperature and electric field should not significantly affect the DC volume resistivity of the insulation material.

2.5. Partial Discharges in Cables

Voids or gas-filled cavities will be formed in the insulation or interfaces of insulation and screens during the manufacturing process. For instance, a void may be formed in the extrusion process of XLPE cables. It is also possible formed by differential expansion and contraction of materials of the cable due to short-circuit.

In general, compared to the bulk of insulation, voids have a higher electric stress but the gas inside the void usually has lower breakdown strength. When the electric stress in the voids exceeds the breakdown strength of the gas inside, it may occur partial discharges. These discharges will weaken the insulation gradually and finally destroy it, leading to breakdown. So the inception voltage for the beginning of the partial discharges is vital.

Partial discharges damage the cable insulation in a variety of ways, such as electronic, chemical and mechanical process. Last but not least, partial discharges can lead to initiation and growth of trees which could cause the destruction of the whole cable.

2.6. Treeing

Treeing is a phenomenon of electrical pre-breakdown. It can occur under DC, AC and impulse voltages. This name is because the path of damage that progresses through stressed dielectric resembles the form which looks like a tree. Such Tree-like discharge patterns could lead to total breakdown of the insulation. It can occur in most solid dielectrics such as glass. For some dielectric like polymers, it is a huge problem.

In organic extruded dielectrics, the most likely reason for dielectric failure is the lengthy aging process. For the initiation and growth of trees, it is necessarily required for electric stress and stress concentration. Under high electric stress in dry dielectrics, trees can growth sharply by periodic partial discharges.

2.6.1. Electrical Trees

In the dry dielectric, electrical trees can be initiated and propagated due to high divergent electric stress under some conditions such as metallic or semiconducting impurities and voids. This tree includes hollow channels which are a result of decomposition of dielectric materials by partial discharges. The tree in PE materials can still be easily observed with an optical microscope. Figure 15 shows electrical trees in XLPE material.

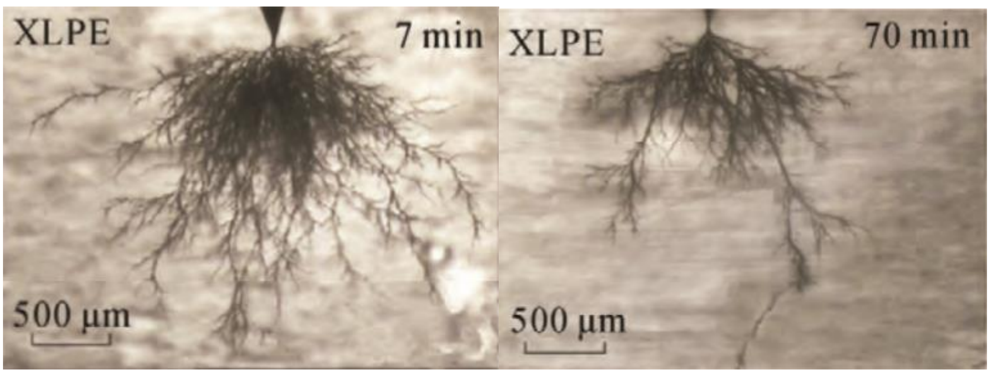

Figure 15 Electrical trees in XLPE [36]

(a) Electrical trees in XLPE at 30℃ *(b) Electrical trees in XLPE at -90℃*

Trees which are starting from within the insulation and progress outwards from electrodes are called bow-tie trees. In contrast, trees which start to grow at an electrode insulation interface and make progress towards the opposite electrode are called vented tress.

Bow-tie trees do not have a free supply of air to support continuous partial discharges. So the growth of such trees is discontinuous and discharge occurs in longer periods of extinction due to the rise of void pressure resulting from ionization. During such extinction period, the gas pressure is reduced and the occurrence of another partial discharge is easier that cause the tree to grow larger.

For the growth of a vented tree, access to free air is a significant factor. This type of trees is capable to continuously grow and could bridge the electrodes or cause a dielectric failure because of their high length. But usually vented trees do not grow long enough to bridge through the whole insulation thickness or cause a failure [3, 4].

In electrical treeing, there are two distinct periods. First is the incubation period during no measurable partial discharges can be defected but a tree-like figure is observed in the end. The incubation period depends on its distribution and the stress level at the initiation site, the properties and composition of the dielectric, and the conditions of the environment. Another is the propagation period during the tree-like figure grows in the insulation and a great magnitude of partial discharge can be measured.

In general, at low-stress levels, the cumulative process is proceeding and will eventually provide conditions that initiate treeing. The mechanisms have been proposed to explain the initiation of electrical treeing include heating, thermal decomposition, partial discharges in voids, the injection and extraction of electrons at the tree site, and mechanical fatigue cracking due to periodic Maxwell stresses [3,4]. It is also believed that the mechanical effects including the buildup of strain, fatigue failure, and fracture due to shockwaves play a significant role in the initiation and growth of electrical trees [5].

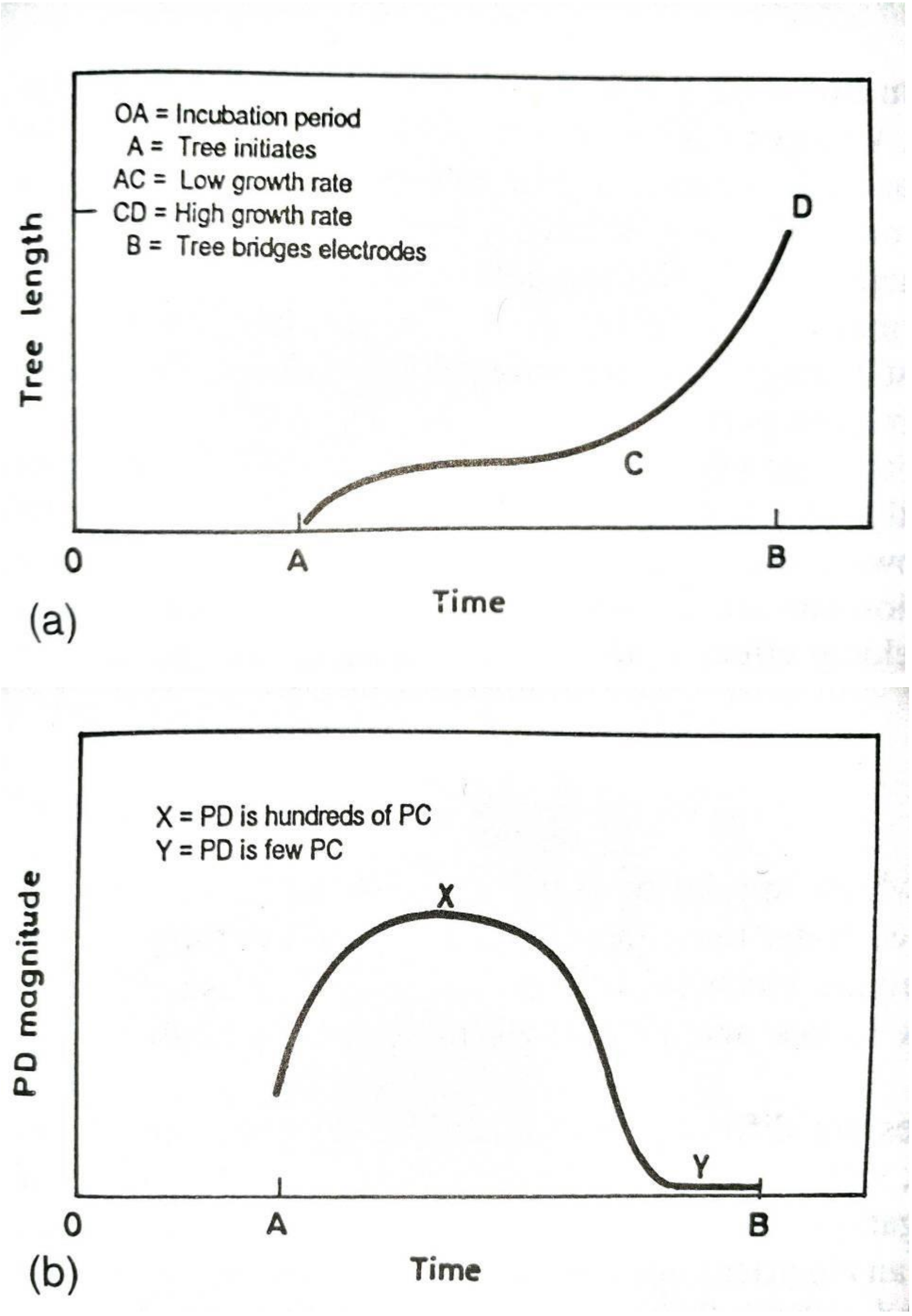

Figure 16 Typical evolution of PD level and electrical tree length [8]

Aging of low-density PE under uniform, divergent fields showed that electrical trees do not progress at fields lower than 20 kV/mm. Local fields around 100 kV/mm are required for initiation of the tree. [6] At working voltages due to various reasons, for instance, stress enhancement, such fields can occur.

After the initiation of the tree growth, a series of sporadic bursts of activity proceeds. For example, more branch of the tree will be shown and the rate of growth falls. Two of the vital factors affect the rate of tree propagation are the development of internal gas pressure due to partial discharges and the shielding effect of neighboring branches on the electric field. The channels of the tree are normally hollow that conducting carbon particles may be included and the diameter of the channel is from a few up to tens of micron meters [6].

2.6.2. Water Trees

In water-exposed polymer-insulated stressed cables, those tree-like figures are called water trees. It occurs in the presence of moisture. Compare to the electrical treeing, water treeing often initialized at a lower electric stress value and progresses slower without any detectable partial discharges.

Different from electrical trees, water trees do no exhibit measurable partial discharges level greater than 0.1pC, and the time of propagation is measured in a unit of years. Their appearance is different too, water trees have relatively few branches than electrical trees. Then, unstained water tress will be invisible when the insulation is dried and electrical trees are clearly visible in such conditions. Last but not least, there are no permanent hollow channels in water trees. Instead, they have filamentary paths between small cavities.

Similar to electrical trees, water trees also have bow-tie type and vented type of trees. Bow-tie water trees are initiated in the volume of insulation and vented water trees are initiated in the surface. They all start to grow from points that have a high electric stress level and they are also moisture or moisture vapor sources. Those vapors maybe from external sources or already contained inside dielectric during the manufacture process.

The concentration and propagation rate of vented trees is usually lower than bow-tie water trees but at the late stage, due to the growth rate of bow-tie trees is significantly drop, its length is restricted, and the propagation rate of vented water trees is now higher than bow-tie water trees. It is worth mentioning that few bow-tie water trees are the origin of the breakdown of the cable and vented water trees are usually capable to bridge the dielectric since they can grow to a sufficient length, they also usually have access to the water. What’s more, the effective insulation thickness may be reduced when such trees grow long enough and when the effective insulation thickness is below the requirement to support the electric stress, failure may occur by electrical treeing. At the tip of water trees or somewhere near the tip, the growth of electrical trees is very often observed [3,4,5,7].

There is water in water trees so if this water is evaporated then the water tree channel becomes invisible. But if the insulation exposed to water or water vapor then the tree will absorb the water again. A vented water tree column near the initiation spot can contain up to 10 per cent of water and the water content in the rest of the tree site may up to 1-2 per cent [9]. The water trees do not totally destroy the insulation, it only weakens it since the water tree channels act as a dielectric but with very poor performance.

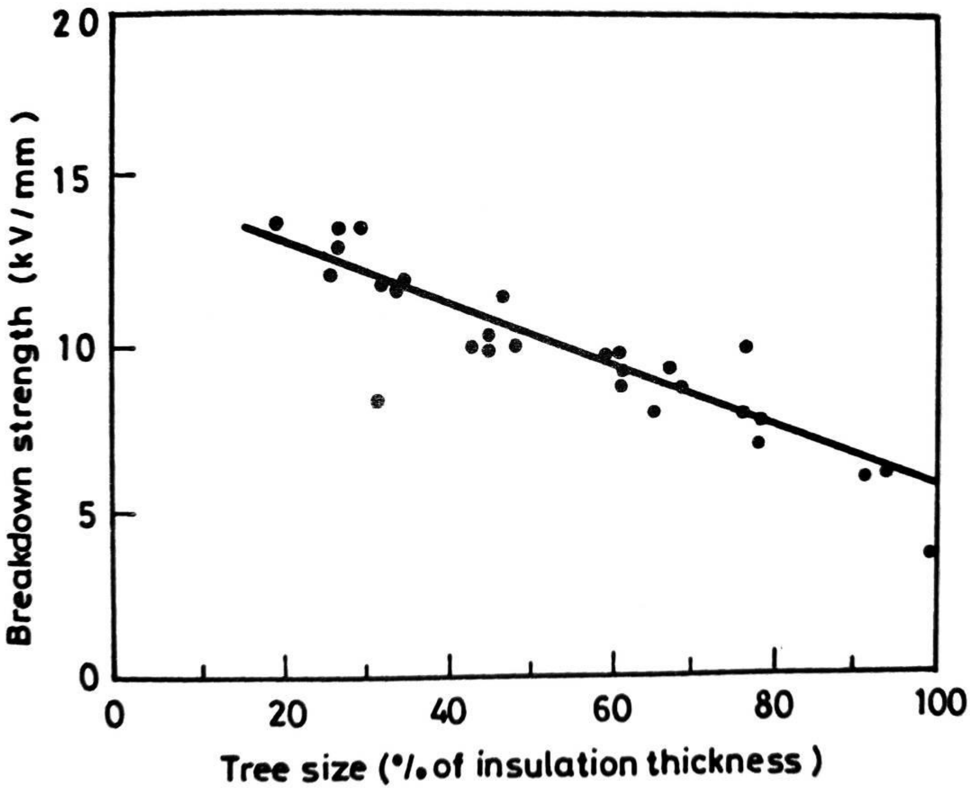

Figure 17 Relation between the mean breakdown stress level and the water tree size [9]

From figure 17, a clear relation between the tree size and breakdown strength can be shown. Even when the water trees have crossed the entire insulation part, the breakdown strength of such dielectric is still above the service stress level of ~2kV/mm so the water trees do not cause immediate breakdown under service conditions.

2.6.3. Electrochemical Trees

Electrochemical trees are special types of water trees which contain minerals or ions. Such minerals or ions penetrate the dielectric under electric stress. Some example like blue and brown trees are caused by sulfur, iron, copper or aluminum ions, sulfide trees caused by H_2S [3,4]. These types of trees are permanently visible, its color depending on the chemistry of ions and the materials of cable dielectric.

2.7. Special problems

2.7.1. Energizing of the cable

For the HVDC cable in the system, the slow ramping of the system voltage is important to prevent high surges. The normal startup with operational inverters must be very careful to prevent oscillations of the series resonant circuit which is formed by cable capacitances and station inductances.

The cable capacitance charging can be assumed to be 0.3~04μF/km to be preferable to be done by linear voltage ramp[2].

2.7.2. Change in Direction of Power Flow

HVDC cable system in operation nowadays change the direction of power flows by reverse the voltage polarity. The solution is the reversal of the direction of current flow by polarity reversal switches but this method has not been deployed again in any system. The reason may be the transient reversal of polarity is still not possible to avoid. The cable must be designed to withstand this increased stress on the dielectric.

2.7.3. Current Reduction Effect

The insulation of HVDC cable is required for a long useful time. Normally is that no partial discharges occur in the cable dielectric which would damage or even destroy the cable. It is recently discovered that with a rapid reduction of the current being transmitted there can be a repaid decrease of the pressure in the cable and finally causing the formation of cavities which is a potential risk of partial discharges that can damage the insulation even at nominal voltage. For the operation of HVDC systems, a restriction to permit the operation only at a constant power or only with a slow change of the power to avoid power reduction effect and the formation of cavities in the insulation is unacceptable.

2.7.4. Overvoltage Stresses

HVDC cables are designed to withstand high overvoltage. But nevertheless, the overvoltage occurs which exceed the dielectric strength of the cable.

2.7.5. Voltage Surges Caused by Lightning

Direct lightning strike on the cable termination is extremely harmful. So, protection equipment with a wide region of safety must be provided to prevent surge caused by direct lightning and back flashover.

2.7.6. Switching Voltage Surges

Switching voltage surges on the AC side can be transferred to DC side. Those switching voltage surges are added by converter bridges connected on DC side in series. But they are limited to safe levels by surge arresters connected to the individual valve and the converter groups of HVDC system in parallel.

2.7.7. Stress Caused by Fast Changes in Voltage

Because of the AC system fault near the station leading commutation failures or the activation of bypass path protection equipment when there is an inverter failure resulting in the collapse of the DC voltage, the rectifier responds with a reversal of voltage polarity. The rectifier will temporarily operate as an inverter to reduce the DC current. This reversal of polarity is a part of the design function of HVDC system. And the cable must be capable to withstand the stress. There are also very rapid voltage changes in direct voltage collapse that will result in a flashover of the insulation in a precipitous subtractive traveling wave in the cable. In some cases, the reflected wave can reach twice as the nominal value in opposite polarity.

2.8. Cable Aging

All cables are affected by electrical, mechanical and thermal stress simultaneously due to high voltages and high currents. And there are chemical changes in those dielectrics as well. Also, chemical changes happen in the surrounding environment. So, it is important to consider different type of stress that affects the cable and even a combination of those stresses in operation.

2.8.1. Voltage Aging

Partial discharges and treeing could reduce the life of the cable. The degradation of materials caused by partial discharges is greatly affected by the applied voltage and frequency. But for DC condition, there is no frequency so the only factor need to consider is voltage. In the existence of cavities and partial discharges, the lifetime of a dielectric is affected by voltage strongly and it follows a relationship of the form:

$$(V^n) * t = Dv \tag{5}$$

where Dv is the voltage life factor and it is a constant, n is depended upon the dielectric material, cable manufacture method, size of the cable, and type of the applied voltage. For cables, n is between 5 and 25 [3,20]. For the MV XLPE cable, n is 9 [6]. Equation (5) is used to estimate the lifetime of cable that is only under voltage stress and it does not count any other type of stresses which will appear in actual operating conditions.

2.8.2. Thermal Aging

The insulation deteriorates faster at elevated temperatures and it is also necessary to consider the thermal stress on cable aging. The temperature affects the materials in the dielectric, causing chemical changes of those materials. Such changes greatly influence the properties of dielectrics and the expected lifetime of cable insulation. The lifetime of the cable is related to temperature by

$$t = G \exp\left(\frac{H}{T}\right) \tag{6}$$

where G and H are constants determined by the activation energy of the reaction, such reaction influences the behavior of dielectric, and T is the temperature in K. To use the equation (6), some parameters such as tensile strength and breakdown strength must be identified along with suitable end-point values that are tracked at various temperatures to calculate the life.

2.8.3. Multifactor Stress Aging

Since it is normal that cables are subjected by various types of stress simultaneously, for instance, electrical, thermal, mechanical, chemical and radiation stress. The result of the lifetime shows a significant difference between a single stress applied to the cable and multiple stresses applied simultaneously on the cable. Now the acceleration of cable aging is more focus on the effects of a group with voltage, temperature, water and chemical factors together.

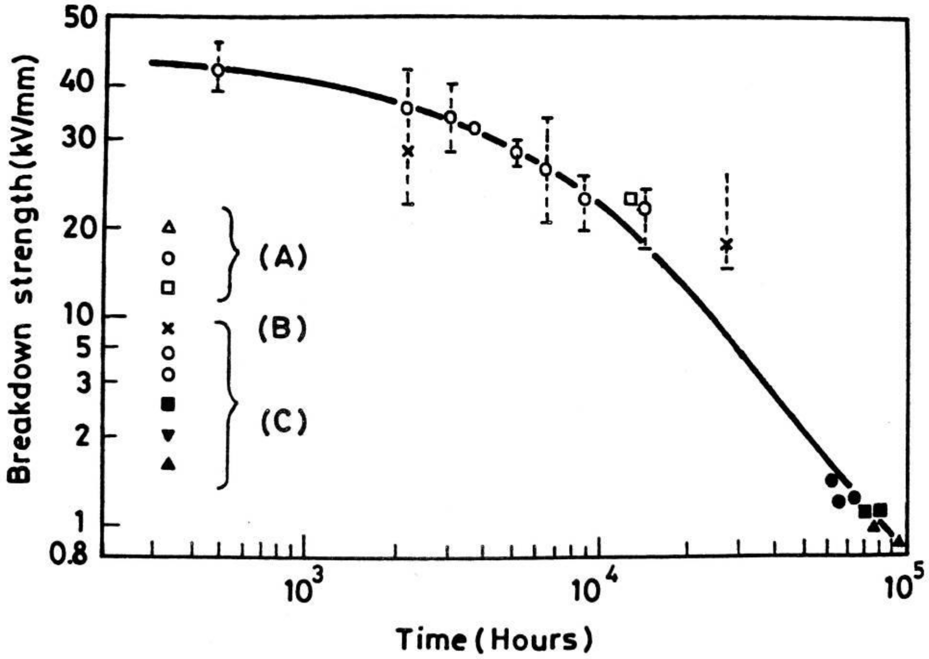

Figure 18 E-t curve of XLPE cable and cables with water trees [10]

Figure 18 shows a voltage-time characteristic for XLPE and PE cables with accelerated aging tests along with cables that are removed from service. It is shown that water treeing shortened the lifetime of cable greatly.

3. Experimental measurement

3.1 Experimental Method

3.1.1 Sample preparation

The sample of XLPE strips was cut from the cable that operates in 22kV directly. The cable was rotating and moving forward while a blade was used to cut the cable and make XLPE strips. Then the rectangle XLPE sample was taken by cutting the XLPE strips using a cutter.

3.1.2 System for measurement

The measurement instrument of dielectric strength in DC voltage for XLPE is shown in figure 19. A transformer box shown in figure 22 was connected to the power grid and supplied the measurement system with high voltage input. The voltage was measured inside the box and shown in the meter with a scale of 0.23 to 80. A diode shown in figure 23 was used to convert AC voltage to DC voltage, the DC voltage supplied is negative. A capacitor shown in figure 24 was used to smooth the voltage and three resistors shown in figure 25 were used to limit the current when breakdown occurs. The sample and electrodes were inside a tank filled with insulation oil. The construction of the electrode system is shown in figure 26. There was a close contact between the sample and two electrodes that has a diameter of 6mm so it means the area of contact is $9\pi\ mm^2$. The oil was special vegetable oil which has a high dielectric strength to prevent surface discharge. But it should be considered that the process of pressing the sample to take out the oil inside the gap and achieve a close contact may cause deformation of the sample.

Also, during the experiment, we meet an issue that the insulation oil may be contaminated due to various reason. For instance, the dust or impurities in the surface of plier which is used to put the XLPE sample into the test area and take it out. Such contamination may cause adsorption of the impurities in the surface of the XLPE sample and form a conductive path that finally lead to a surface discharge and interrupt the dielectric strength test. The conductive path which causing the surface discharge is shown in figure 27.

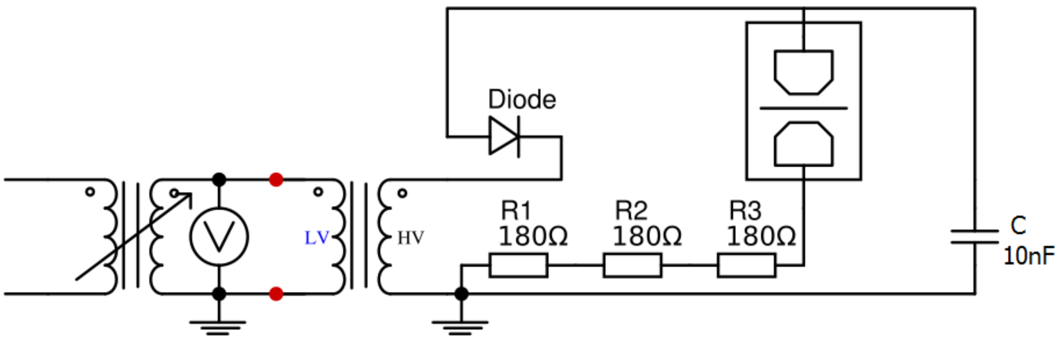

Figure 19 Schematic diagram of XLPE for dielectric strength and Volt-time characteristic under DC voltage

The measurement instrument of dielectric strength in AC for XLPE is shown in figure 20. It was basically the same as the equipment set-up of DC dielectric strength measurement. Just there was no diode to convert AC voltage to DC and there was no need of capacitor to smooth the voltage.

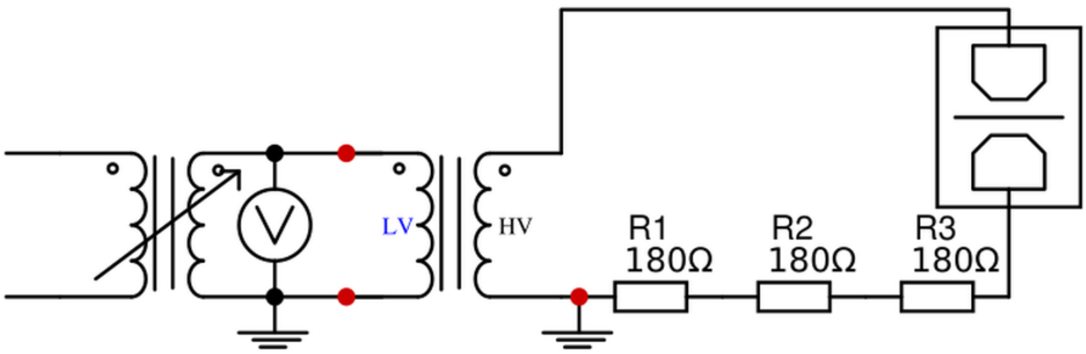

Figure 20 Schematic diagram of XLPE for dielectric strength and Volt-time characteristic under AC voltage

Figure 21 Testing system of XPLE for DC dielectric strength and Volt-time characteristic under DC voltage

Figure 22 Transformer box

Figure 23 Convertor diode

Figure 24 Smoothing capacitor

Figure 25 Current limiting resistor

Figure 26 Electrode system

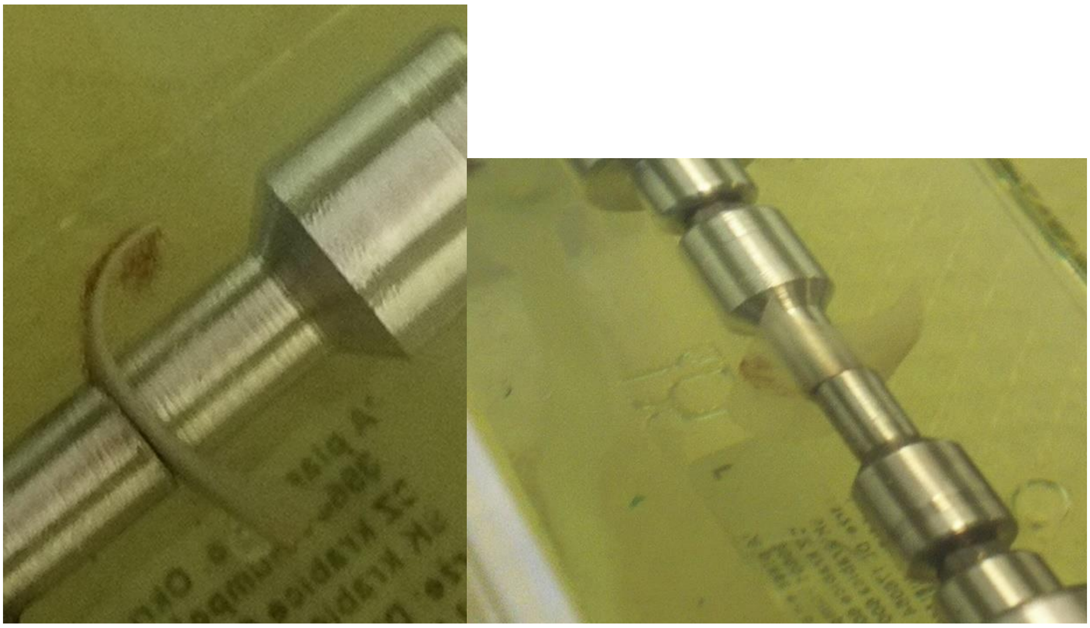

Figure 27 Conductive path formed by impurities under DC voltage which causes surface discharge

3.2 Measurement result

The dielectric strength of XLPE sample under different DC voltage at room temperature is shown in table 1. Where the average value of dielectric strength is 308.72 kV/mm and the standard deviation is 42.24 kV/mm.

Table 1 Dielectric strength of XPLE samples under DC voltage

U[kV]	d[mm]	Dielectric strength[kV/mm]
53	0.22	240.91
56	0.22	254.55
64	0.22	290.91
68	0.2	340.00
68	0.2	340.00
56	0.22	254.55
62	0.19	326.32
72	0.2	360.00
70	0.2	350.00
66	0.2	330.00

The dielectric strength of XLPE sample under different AC voltage at room temperature is shown in table 2. Where the average value of dielectric strength is 89.96 kV/mm and the standard deviation is 7.72 kV/mm.

Table 2 Dielectric strength of XPLE samples under AC voltage

U[kV]	d[mm]	Dielectric strength[kV/mm]
20	0.22	90.91
19	0.21	90.48
19	0.22	86.36
20	0.23	86.96
17.5	0.22	79.55
17.5	0.22	79.55
21.5	0.22	97.73
22	0.21	104.76
18	0.21	85.71
20.5	0.21	97.62

Volt-time characteristic for 0.22mm thickness XLPE sample under DC voltage at room temperature is shown in table 3.

Table 3 Time of breakdown for XPLE samples under DC voltage

Dielectric strength[kV/mm]	Average Time[s]
309.09	392.00
295.45	323.33
272.73	280.00
250.00	1868.00

Volt-time characteristic for 0.22mm thickness XLPE sample under AC voltage at room temperature is shown in table 4.

Table 4 Time of breakdown for XPLE samples under AC voltage

Dielectric strength[kV/mm]	Average Time[s]
81.82	11.33
77.27	100.00
75.00	324.33
72.73	1440.00

Figure 28 shows the dielectric strength versus the time-scale parameter of Weibull distribution under AC and DC voltage of XLPE.

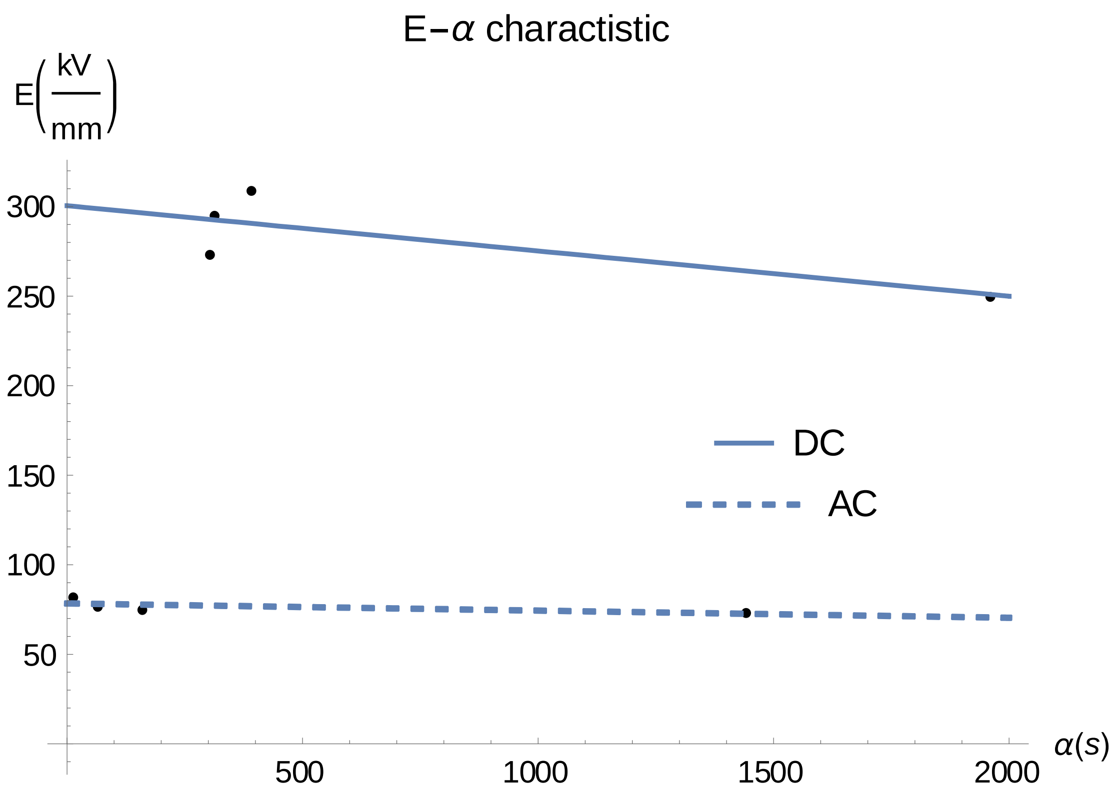

Figure 28 Comparison of DC and AC E-t characteristic

3.3 Conclusion

From the result of dielectric strength for XPLE in AC and DC voltage comparison, the dielectric strength of XLPE under DC voltage is approximately 3 times higher than the case in AC.

From the graph of E-t characteristic, it is obvious that during a relatively short time period, the XLPE shows a better dielectric performance in DC than the case in AC. But the absolute value of slope for DC case is greater than AC and both of them is negative. So, it can be estimated that the line of E-t characteristic for XLPE under DC voltage at a relatively long-time period will finally be overtaken by the line which shows the E-t characteristic under AC voltage.

It is clear that the dielectric strength of XLPE under DC voltage is much higher than the AC case during short time period. But due to the space charge effect and electric treeing inside the insulation that forms conductive path and accelerated the breakdown, in long time period, the aging of XLPE insulation is faster so the performance of insulation under DC voltage is even worse than the AC case.

As a result, the XLPE shows a great dielectric capability under DC voltage so it is sure that XLPE can be a good material of insulation in the construction of HVDC cable transmission system. But the problem connected with space charge and treeing that accelerate the occur of dielectric failure need to be solved by other ways. For instance, nanoparticle add-on is one of the good way and a lot of research and work has already put into it. Also, there are research project focus on other type of material such as PP material to try to avoid such defect of XLPE material.

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Table of figures

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