KTH Electrical Engineering

Conductivity measurement on thick insulating plaque samples

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Abstract:

The conductivity is one of the main properties of HVDC cable insulation materials and needs to be evaluated carefully. Since measurement on cables is time consuming, often thin specimens and normal conductivity measurement cells are used to compare the materials. In this way however, the bulk effects will be less represented in the measurement and the results will be less representative. Instead, one needs to perform the measurements on thick plate samples and with higher voltage levels. This work focuses on the conductivity measurements on thick HVDC insulation plate samples subject to a high electric field and carefully controlled conditions. In the literature, there are many different methods of measuring the leakage current such as dielectric spectroscopy, PD, IV and PEA measurements. In this thesis a three electrode setup is used to measure the leakage current where the electrodes are placed inside the oven. This is to be able to control both temperature and high voltage under similar and different conditions where it is possible to change these two parameters during measurement. This was made by two Labview programs; one for creating a schedule and one control program which controls the equipment in the cell. The task was to make sure that the cell functioned by obtaining repeatable and reasonable measurements. The results that were obtained were reasonable and verified that the cell functioned. The executed measurements were performed in order to achieve a better understanding of error factors in the measurement system, ranging from preparing the sample to measuring the leakage current. The purpose with the cell is it to investigate the quality of the HVDC insulation by conductivity measurements on millimetre thick plate samples.

Keywords: Conductivity, XLPE, leakage current, polarisation, high-voltage, ICE 60093, ASTM D257, voltage and temperature control, electrodes

Sammanfattning:

Den elektriska konduktiviteten är en av de viktigaste egenskaperna av HVDC kablars isolationsmaterial, XLPE, och den måste utvärderas noggrant. Mätning på fullskaliga kablar är tidskrävande och för att jämföra material används istället ofta tunna prover och normerade konduktivitetmätningsceller. En nackdel med denna metod är att bulkeffekterna blir mindre framträdande i mätningen och resultaten kommer att vara mindre representativa. Istället måste man utföra mätningen på tjockare prover och vid högre spänning. Detta examensarbete fokuserar på mätning av ledningsförmåga hos tjocka HVDC-isolationsprover under noggrant kontrollerade förhållanden och starka elektriska fält. I litteraturen finns det många olika metoder att mäta läckströmmar på, till exempel dielektrisk spektroskopi, PD, IV och PEA mätningar för att nämna några. I denna avhandling kommer ett tre-elektrod system att användas där en temperatursensor är monterad på ena elektroden. Systemet används för att både mäta läckströmmar och temperatur vid provet. Detta gör det möjligt att kontrollera temperatur och spänning oberoende av varandra vilket gjordes med hjälp av två Labview program. Det ena för att skapa ett schema och det andra användes som kontrollprogram för att styra utrustningen i cellen. Uppgiften var att kontrollera cellens funktion genom att erhålla rimliga repeterbara mätningar. Mätningarna gav rimliga resultat vilket indikerade att cellen fungerar tillfredställande. Syftet med mätningarna var att få en bättre förståelse för felfaktorer i mätsystemet som kan vara allt från att förbereda provet till att mäta läckström. Syftet med cellen är att undersöka isolationsegenskaperna på millimetertjocka pressade XLPE prover.

Acknowledgements

Here I would like to thank everyone who helped me to complete and around the work. This project was founded by ABB so I would like to gratefully acknowledge them. Regards and thanks to Assoc. Professor Hans Edin at KTH who helped me with his guidance and comments during the work a lot. Regards and thanks to Hossein Ghorbani at ABB HVC who was my supervisor at ABB who helped me with his guidance and comments during the work a lot and guidance around leakage current measurements. I would like to thank Amirhossein Abbasi and Bengt-Åke Karlsson at ABB HVC that has worked with me for building the conductivity cell and provided support. I would like to thanks Sofie Lindalh at ABB HVC who taught me to press plate samples of polymers. I would like to thanks Carl-Olof Olsson at ABB CRC and Marcus Saltzer at ABB HVC who also supported me with material and guidance around leakage current measurements. Finally thanks Marc Jeroense who is the R&D manager at ABB HVC.

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List of abbreviations

XLPE: Cross-Linked Polyethylene
HVDC: High Voltage Direct Current
HVAC: High Voltage Alternating Current
HDPE: High Density Polyethylene
LDPE: Low Density Polyethylene
PEA: Pulsed Electroacoustic
GC: Gas chromatography
GSC: Gas-solid chromatography
GLC: Gas-liquid chromatography
HPLC: High performance liquid chromatography
PD: Partial Discharge
BD: Breakdown
ASTM: American Society for Testing and Materials
HV: High Voltage
IEC: International Electrotechnical Commission
MI: Mass-Impregnated paper
IV: Current-Voltage
HVC: High Voltage Cables

List of symbols

U – Voltage	[V]
R – Resistance	[Ω]
I – Current	[A]
I_{depol} – Depolarisation Current	[A]
I_{pol} – Polarisation Current	[A]
E – Electric field	[V/m]
ρ – Electric resistivity	[Ωm]
σ – Electric conductivity	[S/m]
J – Current density	[A/m^2]
A – Area	[m^2]

1. Introduction

1.1 Background

HV cables have been used for transferring electrical power since the first years of electrical industry. An electrical cable is a simple apparatus consisting of a conductor which carries electrical current, an insulation layer which separates the voltage from ground, and an outer conductive layer which is connected to ground. Other layers are also added for mechanical reinforcement and protection against humidity.

Figure 1.1: An ABB submarine HVDC cable, figure from [1]

Electrically, the most important part of a HV cable is the electrical insulation of the cable. A good insulation makes it possible to reach higher voltages and therefore less current. Hence, a smaller conductor will be required to carry the same amount of electrical energy.

The first major type of insulation for HVAC cables has been oil and paper or MI [2]. The very first HVDC cable, introduced by ABB in 1954, connected the Island of Gotland and main land of Sweden in the Baltic Sea [2]-[4]. Before 1999 when the first HVDC polymeric cables were used, MI cables were the only technology used in DC applications [2].

One of the most important properties of the HVDC insulation materials is their conductivity [5]. An all too large insulation conductivity can result in leakage currents, and non-uniformities in the conductivity distribution in the direction of the electric field can cause local field enhancements and space charge accumulation which can degrade the insulation. Hence, conductivity measurements are of great importance when testing a cable.

Unlike many physical properties, conductivity of insulation materials is not very easy to measure because of several challenges; first, conductivity of XLPE insulation is believed to depend on the amount of polar chemicals such as cross-linking by products in the insulation; using a thin sample the polar molecules can leave the sample and therefore the conductivity will be affected; second, the measured leakage current decreases by time and does not reach a steady state as the conductivity theories suggest, this makes it very hard to assess the conductivity; third, the preparation method of samples also may affect the results, therefore one needs very good understanding of parameters effects and how to control them; forth, conductivity in polymeric insulations depends on temperature and electric field therefore one needs to take these parameters also into account.

Today, conductivity is measured based on leakage current or chemical residual analysis. The leakage current based measurements are performed using one of the following: PD, PEA, IV, dielectric spectroscopy. The chemical residual analysis is performed by GC or HPLC.

The quality of insulation can be readily assessed using PD. Space charges are measured using PEA. Typical current and voltage measurements are made using IV. Polarisation is measured with dielectric spectroscopy. Chemical residual analysis and HPLC provide an indication of there being any residual gas inside the insulation material. More information on PD, PEA, IV, dielectric spectroscopy, GC and HPLC are given in section 2.3.

None of the existing methods provide complete information on the electrical conductivity of the insulation as both insulation temperature and voltage across the insulation are not controlled during the same experiment. For a complete assessment, all above mentioned measurements must be performed which is time consuming and costly. The objective of this thesis is to put forward a measurement setup and measurement method for evaluation of polymeric HVDC materials, especially XLPE allowing a controlled relation between voltage and temperature. This provides a more complete set of information on the leakage current through the insulation. Having the leakage current observations, the insulation conductivity can be calculated. The thesis is not about to characterize the insulation material even if the setup has that purpose, see reference [5] and [6].

1.2 Aim

The aim of the thesis is to develop a measurement system that can measure the conductivity of thick XLPE samples at high voltages in the range of 5-45 kV at temperatures in the range of 20-90 °C. Next, the functionality of the cell is to be verified by obtaining repeatable and reasonable measurements. Finally, the validity of the measurement techniques is to be investigated when altering both initial and on-going temperature and electric field of the experiment.

1.3 Thesis disposition

In section 2, electrical properties of XLPE insulation material in particular electrical conductivity is discussed. The existing measurement techniques and standard methods are presented.

In section 3, the developed measuring setup is presented.

In section 4, the measurement procedure and sample preparation is discussed together with the test program.

In section 5, the results of the measurements are presented.

Section 6 includes the conclusions from the experiments, the project and limitations.

In section 7, possible improvements and future works are listed.

2. XLPE and conductivity

2.1 Cross-Linked Polyethylene, XLPE

XLPE or sometimes abbreviated as PEX is a form of polyethylene with cross-links between the polymer chains. Almost all XLPE cables are based on HDPE and LDPE, but for the XLPE HV cables are mostly made from LDPE.

Cross-Linked Polyethylene, XLPE, is today widely used as insulation for both HVAC and HVDC cables, this is because of lower production and installation costs of XLPE cables in comparison to oil and paper insulated cables and also less environmental impact of polymeric cables [2]. For decades this polymeric insulation was used only in AC cables. XLPE was first introduced as a HVDC insulation in 1998 when ABB installed the first HVDC Light® cable system on Gotland island in Sweden which was put into service in 1999 [2], [5], [7]-[10].

For HVDC cables, conductivity is one of the most important insulation properties which has to be considered. HVDC XLPE is an excellent insulation that meets the requirements for producing HVDC cables. But the cross-linking by-products in XLPE are believed to affect the electrical conductivity of the insulation and contribute to formation of space charge in the insulation under DC voltage [5]. Beside by-products, some of the phenomenon which may affect the aging of the insulation are electrical treeing, polarisation, space charges and partial discharges [5], [9]. The load losses in XLPE DC-cables are primarily due to the ohmic losses in the conductor and the metallic screen; this is because of very low conductivity of the insulation. An XLPE cable can be loaded continuously to conductor temperature up to 90 °C and an emergency rating up to 130 °C, depending on the standard used. The conductor short-circuit temperature can reach up to 250 °C [11].

XLPE is used in medium voltage cables 10 to 30 kV AC and for high-voltage cables from 50 kV up to around 500 kV for both HVAC and HVDC [10]-[12]. The dielectric losses of XLPE insulation are present also at no load. Those losses depend on the operation voltage applied and shall be considered above 100 kV [11].

Single-core cable with lead sheath and wire armour

Three-core cable with optic fibers, lead sheath and wire armour

Figure 2.1: Submarine cables for DC and AC, picture from [11]

2.2 Electrical conductivity, polarisation and space charge

Conductivity is one of the most important properties of insulation materials used in HVDC applications. The conductivity for the insulation should be sufficiently low to avoid significant leakage current through the insulation layer. Conductivity of XLPE is reported to range from 10^{-16} to 10^{-12} S/m at electric fields and temperatures relevant for cable operations [5]. The conductivity should be uniform distributed in the direction of the electric field in order to avoid local field enchantment and space charge accumulation.

Electrical conductivity is a measure of capability of a material to conduct an electric current [13].

Figure 2.2 shows an example of leakage current curve measurement on a plaque sample from which it is possible to calculate the electrical conductivity for the insulation. This is not a simple task as it is both difficult to evaluate the conductivity. This because the leakage current is decreasing over a long period of time [14].

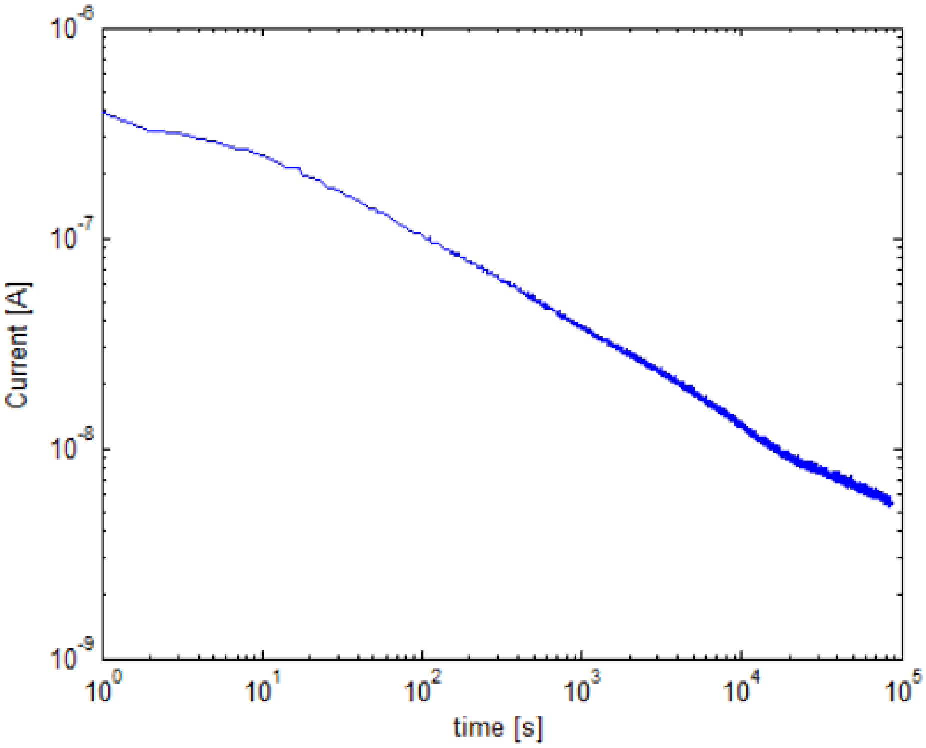

Figure 2.2: “An example of leakage current curve measured on an insulation plaque sample under DC voltage” [14], figure from [14]

Electrical Conductivity σ is expressed as for a conductor/resistor:

$$\sigma = \frac{1}{\rho} = \frac{J}{E} \tag{1}$$

Electrical Resistivity ρ is expressed as for a conductor/resistor:

$$\rho = R\frac{A}{l} \tag{2}$$

These two equations are the basic equations for calculation of electrical conductivity and resistivity in literature [13], [15]. There are standards for measuring surface and bulk conductivity; for this thesis the IEC 60093 standard is used for the measurements. It is an old standard from 1980’s, see reference [16] and the changes that are proposed in previous work will be followed [17], [18]. The techniques and standards for measurement of conductivity will be further discussed in section 2.4.

Other things that can affect the measured current are the polarisation in polymer. When polymer is exposed to an electric field, it may respond in a more varied manner and a whole set electrical effects may be observed [9]. For example polarisation phenomena resulting from distortion and alignment of molecules under the influence of an applied field becomes apparent [9].

When an electric field is applied to an insulating polymer the current can be summarized to “The Four Fundamental Parameters” which can be separated in two main parts:

- Dielectric Properties:

  Parameters that characterize dielectric properties are the “Dielectric constant” which representing polarisation and “Tangent of dielectric loss angle” representing frequency loss [9].

- Bulk conductive properties:

  Parameters that characterize bulk conductivity properties are “Dielectric strength” representing breakdown phenomena and “Conductivity” representing electrical conduction [9].

The term space charge usually taken to mean uncompensated real charge generated in the bulk of the samples as a result of 1) charge injection from the electrodes, 2) field-assisted thermal ionization of impurities in the bulk of the dielectrics and 3) application of a mechanical/thermal stress [18]. Space charges can occur on a variety of factors in insolation such as electrical treeing, vacuum polarisation, breakdown thresholds in the polymer, aging, conductivity and temperature gradient [9], [19], [20].

Electric conductivity of polymer insulations has an exponential relationship with the temperature. The current in the cable conductor creates a temperature gradient across the cable insulation. The temperature gradient can lead to formation of space charge in the insulation. The phenomena known as “field inversion” can occur if the gradient for the conductivity is sufficiently large. This is when the electric field for the outer Semicon becomes even higher than for the inner Semicon [20]. When designing cables this aspect is taken into account but it cannot be predicted easily. Space charge accumulation generally is claimed to be the main factor accelerating degradation of polymeric insulation in HVDC [21]-[24]. Space charge is also an effect of aging this is because that the chemical-physical structure of the insulation is modified through an aging process [20].

Space charge can be detected by using the PEA method on cables if using the modifications according to this reference [25].

2.3 HVDC insulation Characterization methods

There are many different ways of measuring technics and standards which are in to test HV cable insulations. The most common methods that is used for testing insulation material is to use either or both electrical measurements and residual analysis. A short introduction of the most common measurement methods and standards.

2.3.1 Gas chromatography (GC)

Gas chromatography (GC) was invented in early 1900 by Mikhail Semenovich Tswett as a separation technique to separate compounds [26]. There are two types of gas chromatography gas-solid chromatography (GSC) and gas-liquid chromatography (GLC). GSC is based on a solid stationary phase, while GLC is useful for separating ions or molecules [27]. GLC is the more common to use because of limited applications in a laboratory for using GSC [26].

The method for GLC is that the sample first is vaporized and injected into the carrier stream. The sample is transported through the packed column by the flow of inert gaseous mobile phase [27], [28]. The packed column contains a liquid stationary phase which is adsorbed onto the surface of an inert solid [28]. The detector is the device located at the end of the column which provides a quantitative measurement of the components of the mixture as they elute in combination with the carrier gas [26]. In HV cable industry, this GC is used to measure the concentration of polar substances such as cross-linking by-products in polymer insulations.

2.3.2 High performance liquid chromatography (HPLC)

High performance liquid chromatography was introduced late 1960s. But at that time it was known as “High pressure liquid chromatography” which was changed later because the pressure was not a desire rather an unavoidable drawback. With the name changed the HPLC focusing on the very good separations obtained [29]. HLPC builds on the same principle as GC with the difference that pumps is used to generate the flow in the columns with pressure [30]. HPLC is useful to measure the concentration of reactive molecules such as Antioxidants and cross-linking peroxides.

2.3.3 I-V measurement

I-V measurement or current-voltage characteristics are a set of graphical curves which define its operation [31], where the current is a function of the voltage. The relationship of the I-V curves show the current flowing through an electrical or electronic device and the applied voltage across. I-V curves are generally used to determine the basic parameters to a device for an example an ideal resistor. Which also can be used as mathematical model for determine an electrical circuit [31]. Figure 2.3 shows I-V characteristics of four devices one with a large resistance, one with small resistance, a diode and a battery [32].

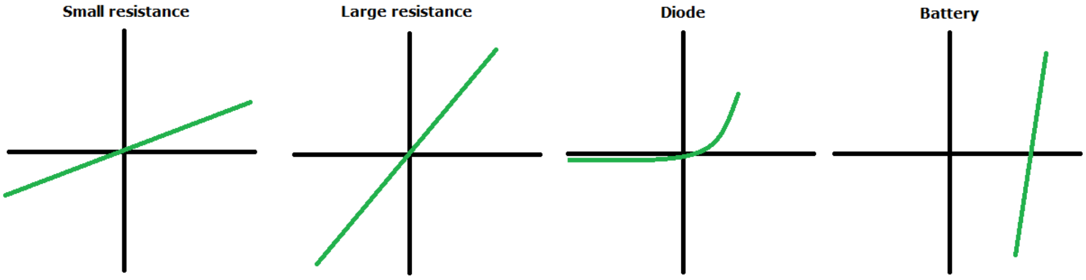

Figure 2.3: The current–voltage characteristics of four devices

The figures show a linear characteristics with a slope S=1/R which for an ohmic component is a straight line. But in the case when the characteristics are not linear it is defined as the “differential resistance”, also known as “incremental resistance” or “slope resistance”. Figure 2.4 shows an illustration of the differential changes where the resistance is changing with the voltage [33]. The figure to the left illustrates the case for low voltage and the right figure shows the case for high-voltage.

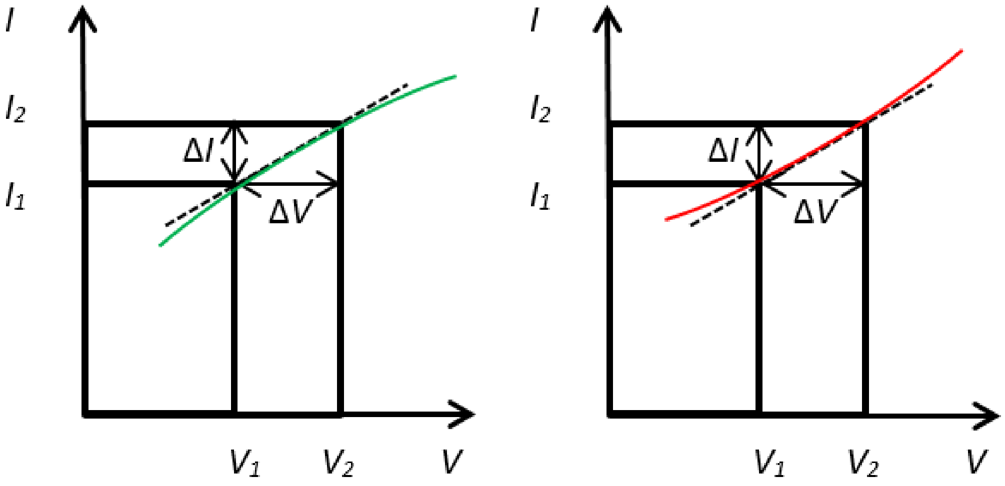

Figure 2.4: Illustration of the differential changes of the current and voltage for both low- and high-voltage

Characterization of I-V measurements of HVDC cables is well described in [34] and [35]. The thresholds that characterize the curves are of particular interest. From these curves, the electric field and current density characteristics may also be studied. This is performed in [34], [35].

2.3.4 Pulsed Electro Acoustic (PEA)

A Pulsed Electro Acoustic space charge measurement is a non-destructive measurement technique from the early 1980s for investigating the space charges in the insulation materials [36], [37]. Figure 2.5 shows the PEA method principle.

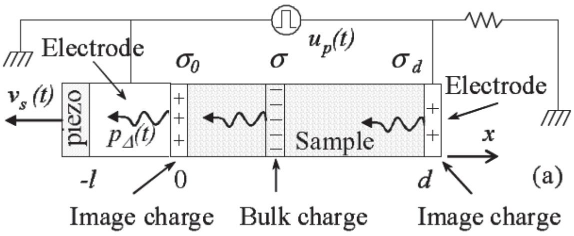

Figure 2.5: Shows the principle of the PEA method, figure from [36]

The principle of the PEA method which can be explained from this reference [38] where Tatsuo Takada describe it by: “When a voltage pulse is applied to a dielectric in which space charges are distributed, the electric field due to the pulse acts on each charge, causing a displacement from its original position. The displacement generates an acoustic wave. The density and polarity of the space charge can be obtained from the physical characteristics of the acoustic wave.” [38].

Measurements of space charge can provide information about “the actual electric field distribution and an indication of the aging state of the insulation” [2].

2.3.5 PD - Partial Discharge measurements

One of the more common processes that cause failure in the high voltage cables are Partial Discharges (PD). PD occurs not only for high-voltage cables it also occurs for example switchgear, bushings, high-voltage transformers, and in stator bars [39]-[46]. Partial discharge is an electric discharge or a small electric spark that occurs inside a void within the insulation. PD occurs from voids, cracks, gaps, similar defects and for solid or liquid dielectrics. It is not possible to predict a PD or predict when a partial discharge can occur anytime in the insulation whereas the electric field strength exceeds the breakdown strength in insulation. It is important to monitor the PD because if it continues it will erode the insulation and develop tree-shaped patterns, known as electrical tree and eventually breakdown (BD). When a partial discharge occurs it is an indication that the insulation begins to fail and that the device is damaged or it is time to replace it [39]-[46].

PD tests on HV cables can give information about the quality and health of the insulation. It is important to monitor the HV cables over a longer period in order to observe the PD development and thus see if HV cable needs to be repaired or replaced [39]-[46]. There are many ways to measure PD; it depends on the environment and object. PD can be detected by:

- “Electromagnetic emissions, in the form of radio waves, light and heat”
  The measurement method used for this is “Transient Earth Voltage (TEV) Sensors” [39].
- “Acoustic emissions, in the audible and ultrasonic ranges”
  For measuring surface PD activity is “Ultrasonic Sensors” used and for internal PD activity is “Ultra High Frequency (UHF) Sensors” used [39].
- “Ozone and oxide of nitrogen gases” UHF is also used for measuring PD discharges in gas insulated assets [39].

2.3.6 Dielectric spectroscopy

There are various methods of Dielectric spectroscopy to measure the dielectric properties of a medium. The methods can be categorized in the time domain and in the frequency domain [46]. The purpose of a dielectric response measurement is to obtain the object's complex capacitance and its frequency dependence. With the help of the real and imaginary capacitive current, and a sample object, its real and imaginary capacitance can be calculated. These capacitance values vary with frequency. It is frequency dependence that is of interest because it can provide information about a material condition. The real capacitance is known as C' and the imaginary is known as C'' [46]-[49].

The equivalent circuit in Figure 2.6 can describe the test object that is of interest, for example a cable [48]. C$_0$ is the geometric capacitance of the test object [46], [48].

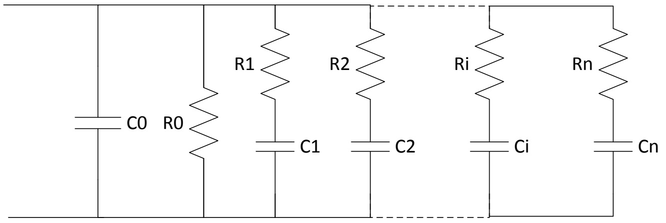

Figure 2.6: Equivalent circuit to model a linear dielectric

The expression for dielectric in vacuum is [48]:

$$D(t) = \varepsilon_0 E(t) \tag{3}$$

But if the vacuum is replaced by another dielectric material will the displacement be increased by the polarisation of the dielectric [48]. Then the expression is:

$$D(t) = \varepsilon_0 E(t) + P(t) \tag{4}$$

Where P is the polarisation.

The capacitances for the real and imaginary are decided from the polarisation and depolarisation current. Which from Maxwell's equations can derive an analytical expression in time domain.

In time domain, the measurements for polarizstion and depolarisation current is the most common method, which can be expressed for the dielectric response current [46], [48]:

$$i(t) = \mathrm{C}_0 \left[\frac{\sigma}{\varepsilon_0} U(t) + \varepsilon_\infty \frac{dU(t)}{dt} + \frac{d}{dt} \int_0^\infty f_{diel}(\tau) U(t-\tau) d\tau \right] \tag{5}$$

Where ε_0 is the permittivity of vacuum and $f_{diel}(t)$ is the dielectric response function [46], [48].

One form of expression for the polarisation current is if using equivalent circuit model in Figure 2.6 will be:

$$I_{pol} = \frac{U_0}{R_0} + \sum_{i=1}^{n} \frac{U_0}{R_i} e^{-t/\tau_i} \tag{6}$$

Expression for the depolarisation current will then be [48]:

$$I_{depol} = \sum_{i=1}^{n} \frac{U_0}{R_i} e^{-t/\tau_i} = \sum_{i=1}^{n} A_i e^{-t/\tau_i} \tag{7}$$

The amplitude has the expression [48]:

$$A_i = U_0 \frac{(1 - e^{-T_c/\tau_i})}{R_i} \tag{8}$$

Another approach is to look in the frequency domain, where there is a stationary relation between voltage and current phase [46]:

$$\tilde{I} = j\omega C_0 \left[\left(\varepsilon_\infty + \Delta\varepsilon_r'(\omega) \right) - j \left(\varepsilon_r''(\omega) + \frac{\sigma}{\omega\varepsilon_0} \right) \right] \widetilde{U} = j\omega(C'(\omega) - jC''(\omega))\widetilde{U} \tag{9}$$

The complex permittivity $\varepsilon_\infty + \varepsilon_r'(\omega) - j\varepsilon_r''(\omega)$ is related to the response dielectric function [46], [48]:

$$\Delta\varepsilon_r'(\omega) - j\varepsilon_r''(\omega) = \int_0^\infty f_{diel}(\tau) U(t - \tau) d\tau \tag{10}$$

Whereas $\tilde{C}(\omega) = C'(\omega) - jC''(\omega)$ is the complex capacitance [46], [48]. In literature will the final analytical expression for the complex capacitance be [48]:

$$\tilde{C}(\omega) = \frac{Y(\omega)}{i(\omega)} = C_0 + \frac{1}{j\omega R_0} + \sum_{i=1}^{n} \frac{C_i}{1 + j\omega R_i C_i} \tag{11}$$

Where the real part is [48]:

$$C'(\omega) = C_0 + \sum_{i=1}^{n} \frac{C_i}{1 + (\omega R_i C_i)^2} \tag{12}$$

Imaginary part [48]:

$$C''(\omega) = \frac{1}{\omega R_0} + \sum_{i=1}^{n} \frac{R_i C_i^2}{1 + (\omega R_i C_i)^2} \tag{13}$$

2.4 DC Conductivity measurements

One of the most relevant measurements on the insulation material for DC is measuring its conductivity on plaque samples. The most common method to use for plaque samples is the three electrode system which is used in this thesis as well.

The DC characteristics of an insulation material are determined by the conductivity. This can be evaluated on several types of test samples, moulded cups, model cable and full-scale cable [6]. In literature, the most common method to measure conductivity and resistivity on plaque sample is to use the three electrode guard system [5], [6], [16], [17], [18], [48], [51]. Figure 2.7 shows the schematic for the circuit of a three electrode system, where there is one electrode for the high voltage, one for the measurement and one guard electrode.

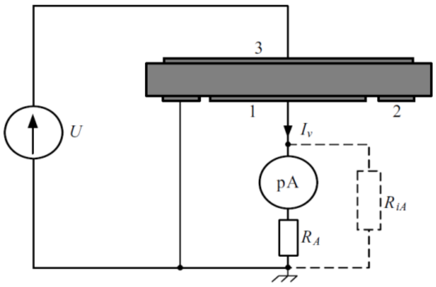

Figure 2.7: “Scheme of the circuit for the measurement of volume resistance in a three-electrode system. Electrodes: 1, measurement; 2, guard; 3, voltage. U is the supply voltage and I_v the volume current” [17], figure from [17]

The electric conductivity should be low in order to avoid high leakage current through the insulation layer [48]. The conductivity for the insulation in a cable is dependent on the electric field, temperature and the local composition of the insulation material [6], [48]. The conductivity increases with the temperature and electric field. Another aspect of the insulation is that the conductivity gradient should be small to avoid space charges within the insulation [6].

Due to low cost and shorter testing time, smaller samples are favourable [6]. But there are some challenges with the plaque sample studies which have to be overcome [14]. The cables have much thicker insulation than typical plaque samples; besides, they have different production procedures which may lead to different behaviours [14], [52]. The electrode material is also a factor that can give different results on the plaque samples [6], [14].

It can be challenging to evaluate the conductivity since as shown in Figure 2.2 the leakage current decreases over a long period of time [14]. Because of that, it is hard to assign a value for the conductivity to a material based on a measurement as such. This is valid even for other DC measurements such as space charge measurements [14].

The electrodes are usually of Rogowski[1] type which can be of several different setups and materials [6]. When using three electrode systems, there are two standards that may be followed for measuring resistance, conductivity and resistivity. These are the international standard IEC 60093 and the American standard ASTM D257 [16], [51].

2.4.1 Standards IEC 60093 & ASTM D257

The international standard IEC 60093, “Methods of test for volume resistivity and surface resistivity of solid electrical insulating materials” and the American standard ASTM-D257, "Resistance DC or Conductance of insulating material" describe the electrode systems for the volume and surface measurements for measurement of resistance, resistivity and conductance [16], [17], [18], [51]. There are four types of electrodes that these two standards describe “circular”, “rectangular”, “tubes” and “square” types of electrodes [16], [51]. According to the standards there are three electrodes; one HV big disk electrode, one guard ring electrode and one smaller measurement electrode. Neither of the standards mention the geometry of the electrodes more than that the guard electrode diameter should at least be ten times the thickness of the specimen usually 25 mm according to the standard [16]. For both volume and surface resistivity, the sample may have any practical form that allows the use of a third electrode to guard against error from the surface effects in the case of volume measurements or volume effect when using surface measurements [16], [51].

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[1] “Rogowski developed a technique that starts by determining a realizable field, then constructing an electrode shaped so that the surface of the electrode lies on an equipotential surface” [53].

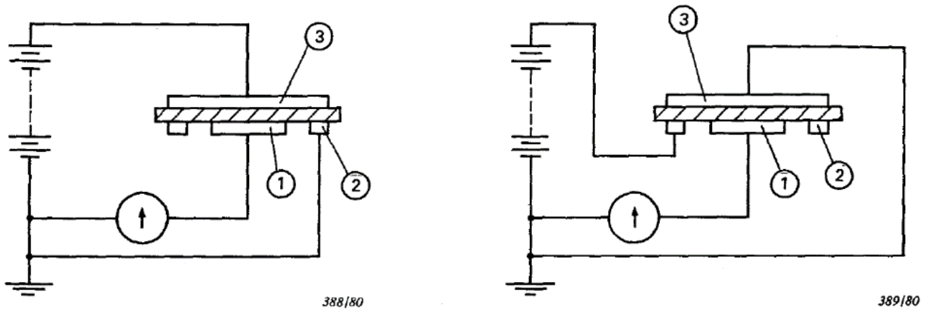

Figure 2.8: The figure to the left shows the setup for volume- and the right for surface resistivity, figure from [16]

Figure 2.8 shows the measurement setup for the volume and surface resistivity that should be used according the standards [16], [51]. The air gap g between electrode no. 1 and no. 2 should be at least twice the sample thickness. Normally the smallest practicable air gap is 1 mm between the electrodes [16], [51]. According to the standards may the electrodes be of different materials where the standards suggest to use materials such as conductive silver paint, sprayed metal, evaporated or sputtered metal, liquid electrodes, colloidal graphite, conducting rubber and metal foil [16], [18], [51]. It can be an advantage to use two different electrode materials or two different methods of applications to see if appreciable error is introduced [51].

2.4.2 Measurement of volume and surface resistivity

Figure 2.8 shows the basic connection circuit for the volume and surface resistivity measurements. For volume system measurements, electrode no. 3, the big disc electrode is connected to DC high voltage and electrode no. 1, the small disc electrode measures the current [17], [51]. The outer ring electrode, electrode no. 2 acts as the guard electrode which guards the volume - and surface current on the outer surface of the specimen for preventing the measurement to be affected from electrode no. 3 to electrode no.2 [17], [51].

For surface conductivity measurement, the electrode no. 2 is connected to DC high voltage and electrode no. 1 measures the current [17], [51]. This time, electrode no. 3 is the guard electrode which guards the volume and surface current from electrode no. 2 and no. 3.

To calculate the surface and volume resistivity are the following formulas used:

- Volume resistivity:

$$\rho = \rho_v = R_x \cdot \frac{A}{h} \tag{14}$$

Where ρ is the volume resistivity in ohms meters, A is the effective area of the guarded electrode in square meters, R_x is the volume resistance in ohms and h is the average thickness of the sample in meters [51].

- Surface resistivity:

$$\sigma = \rho_s = R_x \cdot \frac{A}{g} \tag{15}$$

Where σ (IEC); ρ_s $(ASTM)$ is the surface resistivity in ohms meters, R_x is the surface resistance in ohms, p is the effective perimeter in meters of the guarded electrode for the particular electrode arrangement employed and g is the distance in meters between the electrodes [51].

The volume and surface resistance is determined by the following formula [51]:

$$R_x = \frac{U_x}{(I_s \pm I_0)} \tag{16}$$

Where I_0 is the short-circuit current in amperes, I_s is the steady state current in amperes during electrification and U_x is the applied voltage in voltage [51].

Figure 2.9 shows an example of electrode arrangement on plaque specimen, in this case for circular electrodes [16], [51]. From these two figures the dimension of the electrodes can be determined and the parameters needed for calculating the surface and volume resistivity.

Appendix A at page 37 in the standard IEC 60093, explains how the area A and the effective perimeter p should be calculated. The same equations can be found at page 8 in ASTM D257 standard. In the thesis is circular electrodes used so the equations that should be used to calculate the area and effective perimeter are for circular electrodes [16], [51]:

- Volume

$$A = \frac{\pi(d_1 - g)^2}{4} \tag{17}$$

- Surface

$$p = \pi(d_1 + g) = \pi D_0 \tag{18}$$

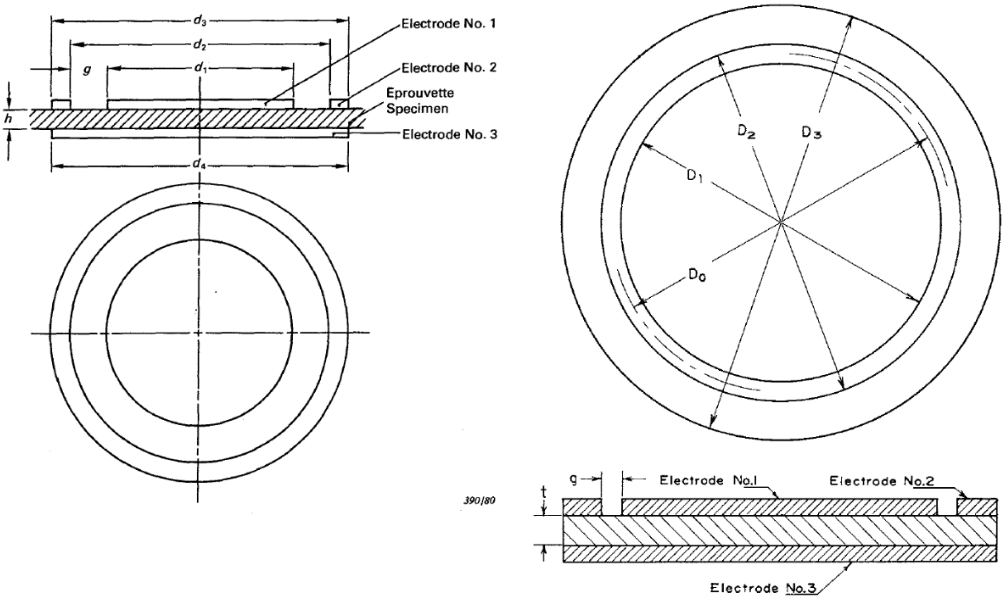

Figure 2.9: Example of electrode arrangement on flat specimen. The left figure shows the standard IEC 60093 and the right standards of ASTM D257-07, figures from [16] and [51]

When calculating the volume resistivity, there are some assumptions that must be taken into consideration. The effective surface area of the electrode is always larger than the geometrical surface of the electrode [17]. This relation is associated with the edge effect which also appears in three electrode systems [17]. In both IEC 60093 and ASTM D257 standards, this is mentioned and it is assumed that the guarded electrode fringing effectively extends by g/2 [16], [17], [51]. But in reality the edge effect is not that large and is smaller than g/2 [17]. This is mention in the appendix of the ASTM D257 standards which can be found in Appendix X2 “EFFECTIVE AREA OF GUARDED ELECTRODE” at page 15 [51]. The fringing (correction of the air gap) can be estimated from this expression [17], [51]:

$$\frac{g}{2} - \delta \tag{19}$$

where:

$$\delta = \frac{2h}{\pi} \ln \cosh \left(\frac{\pi}{4} \frac{g}{2} \right) = \frac{2t}{\pi} \ln \cosh \left(\frac{\pi}{4} \frac{g}{2} \right) \tag{20}$$

The correction of the air gap g may also be written as:

$$g\left(1 - \frac{2\delta}{g}\right) = gB \tag{21}$$

where B is the fraction of the gap width to be added to the diameter of circular electrodes or to the dimensions of rectangular or cylindrical electrodes” [51]. B can be solved from this expression [17]:

$$B = 1 - \frac{2h}{\pi} \ln \cosh \left(\frac{\pi}{4} \frac{g}{2} \right) \tag{22}$$

The expression that should be used for calculating the surface for the volume resistivity with correction of the gap is [51]:

$$A = \frac{\pi (d_1 - Bg)^2}{4} \tag{23}$$

The correction can also be made with the FEM method in Matlab for example.

2.4.2.1 Measurement setup for measuring small currents

The two standards mention or suggests three methods/setups for measuring small currents on small flat specimens [16], [18], [51]:

- Voltmeter-ammeter method, figure 1
- Wheatstone bridge method, figure 2
- Ammeter method, figure 3 [16]

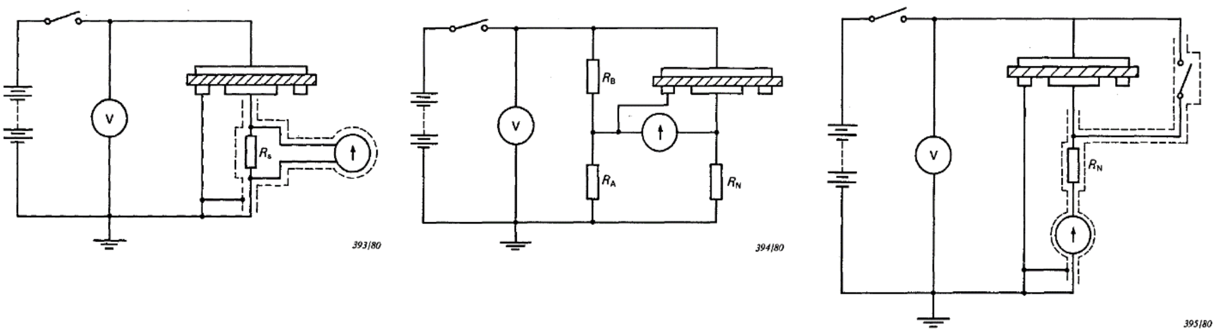

Figure 2.10: First figure shows the voltmeter-ammeter method, the second shows the Wheatstone bridge method and the third shows the ammeter method for volume and surface resistivity, figures from [16]

In voltmeter-ammeter method, the voltmeter measures the applied voltage in the area of DC voltage. The ammeter that measures the current may be a galvanometer, an electric amplifier instrument or an electrometer.

The Wheatstone bridge method uses a typical bridge setup where the electrode with the plaque sample becomes the unknown resistance R_X. Where R_B is changed in decade steps, R_A is used to balance the adjustments and R_N is the fixed resistance during the measurement. R_X is calculated by:

$$R_X = R_N \frac{R_B}{R_A} \tag{24}$$

The detector should be a DC amplifier with high resistance compared to the other resistors.

Ammeter method uses a known value on R_N and a switch that can short-circuit the unknown resistance R_x. When the switch is opened, it is very important that the resistance R_N to be much higher than R_X, $(R_x \ll R_N)$ this is in order not to affect the measurement of the latter [16]. R_N should always be in the circuit this to protect and limit the current to the measurement device in case of a failure or a breakdown in the specimen [16].

Out of these three methods, the voltmeter-ammeter is the most common method to use when measuring leakage current on plaque samples [18].

3. Conductivity measurement setup

In this project a newly built conductivity cell at ABB High Voltage Cables (HVC) in Karlskrona was programed and used. Labview was used as the programming platform for the control and measurement of the setup.

Figure 3.1 illustrates the conductivity cell that is in place at ABB HCV Karlskrona.

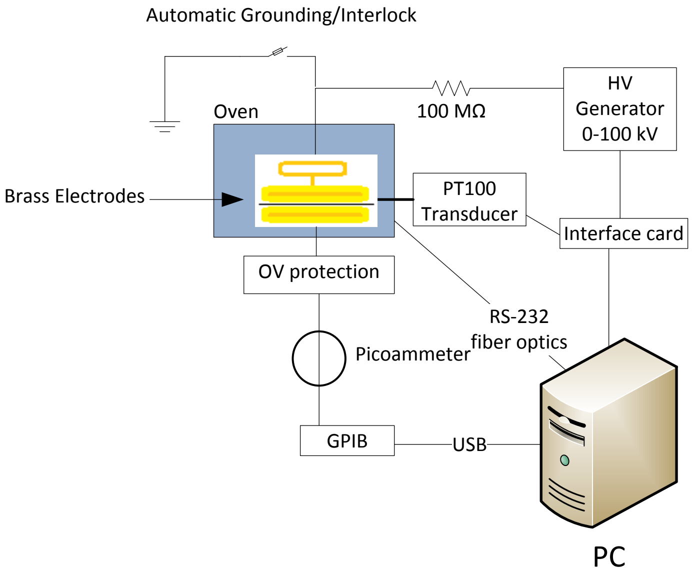

Figure 3.1: Setup of the system

The equipment used in the cell:

- Memmert oven UFB600
- Spellman high-voltage generator 100 kV, 300 W, 3 mA
- Keithley Picoammeter KE6485 Meter
- DAQ 6024E PCI-card from NI
- NI GPIB (IEEE 488)
- PT100 temperature sensor
- PHOENIX transducer PT100 MINI MCR-SL-PT100-UI
- PHOENIX power supply for the transducer MINI-PS-100-240AC/24DC/2

In this setup, the PC controls all the equipment in the cell. It controls the HV source and the PT100 transducer that measures the temperature on the brass electrodes, via an interface card that is connected to the DAQ-card from NI[2] on the PC. The computer communicates with the oven via RS-232 protocol and the connection is made using fibre optics. The HV source is connected to a HV resistor of 100 MΩ that is placed for protection between two isolators shown in Figure 3.2 to limit the short circuit current in the system. The automatic ground is connected to the second isolator in the Figure 3.2 is located there for security reasons to make sure that that the HV is off and that there is no residual charge remaining in the system so it is safe to enter the room. Furthermore, the right isolator is connected to the isolator inside the oven which in turn is connected to the brass electrode, see Figure 3.3. The brass electrodes is connected to the overvoltage protection via a coaxial cable. The overvoltage protection is there to protect the measurement equipment and has the same function as R_N in the ammeter method. The picoammeter

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[2] National Instrument

is connected to the OV protection by coaxial cable and communicating with the PC with the interface protocol GPIB[3] which is plugged into the PC by the USB port.

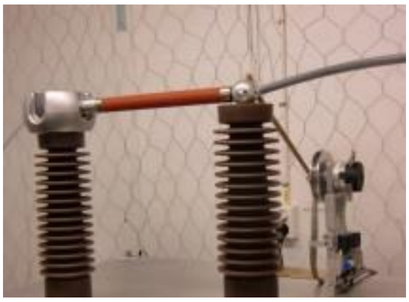

Figure 3.2: Automatic ground and high-voltage resistor 100 MΩ

Figure 3.3: Brass electrodes connected to the insulator

For comparison of the conductivity cell, a round robin[4] was prepared together with Borealis AB in Stenungsund and ABB CRC[5] in Västerås. More about the round robin and measurement setup in section 3.1 and 5.2.

3.1 Measuring setup

The electrode system that is used in the cell used in this work is shown in Figure 3.4. This electrode system was developed by ABB as shown in Figure 3.5 the differences between the cells are that the one at ABB CRC is heated by oil while the cell at HVC and Borealis is heated in an oven [5], [6]. More details on the three electrode system at ABB CRC are described in reference [5].

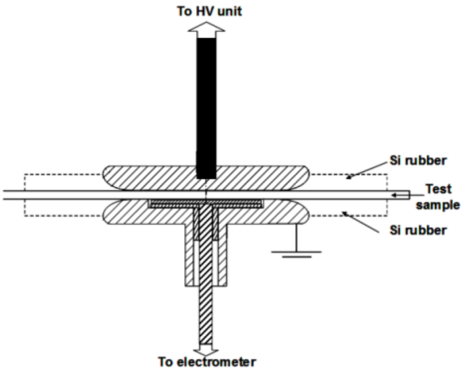

Figure 3.4: The electrode system that is used in Borealis and ABB HVC, figure from [6]

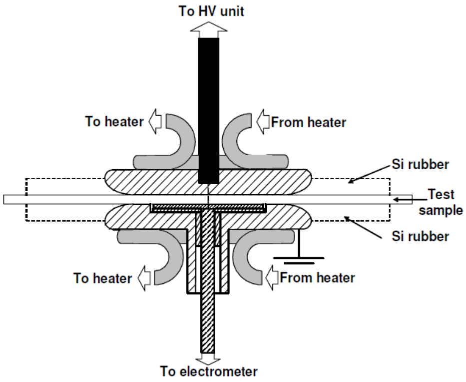

Figure 3.5: Electrode system in ABB CRC, figure from [5]

A closer look at the electrodes is shown in Figure 3.6. The upper electrode is where HV is applied. The leakage current that is passing through the sample into the measurement electrode is measured. A guard electrode surrounds the measurement electrode to reduce edge effects and surface leakage [18].

The difference between an ordinary three electrode system and this three electrode system is that in this system, the guard electrode covers the whole measurement electrode and the air gap is filled with Teflon. The measurement electrode is better protected compared to the ordinary measurement electrode that has

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[3] General Purpose Interface Bus

[4] Round robin test, an interlaboratory test performed independently several times.

[5] Corporate Research Center

an open air gap between the guards. The electrodes are made of brass and are Rogowski shaped which have a diameter of 200 mm and the measuring electrode diameter is 100 mm [6].

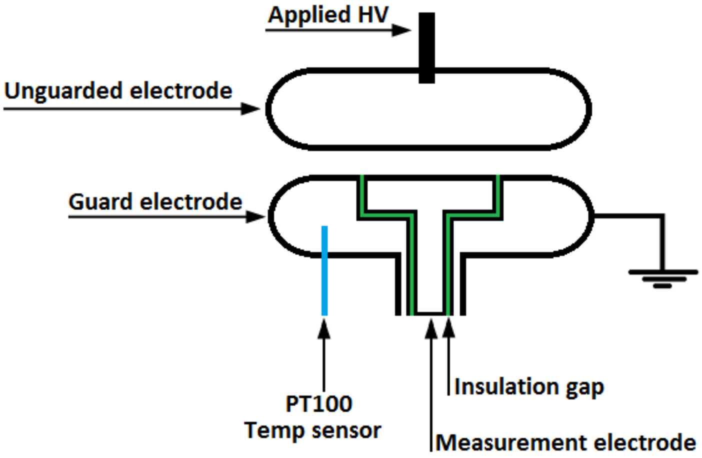


Figure 3.6: Electrode system.

When measuring leakage current, it is important that the surface of the electrodes are clean when changing the sample and that there are no particles left over from the previous sample. If these measures are not taken, it can affect the next measurement and can cause arcing or a breakdown during the measurement.

The lower electrode is connected to a PT100 temperature sensor that measures the temperature on the electrode.

A high voltage resistor of 100 MΩ limits the short circuit current in the system and the maximum allowed current at 100 kV is 1 mA.

The measurement signal is filtered and passed through a protection circuit before the picoammeter. The leakage current measurements are performed by the picoammeter from Keithley [6].

3.2 Labview programing

Two separate programs were developed: one for making a temperature and voltage schematic, and one for controlling the setup according to the schematic and for measuring the leakage current. The programming mainly took place during a summer internship which was made prior to starting the thesis.

The second program loads a preprogramed schedule, control the oven temperature and the voltage according to the schedule and at the same time log the measured leakage current. The program saves the oven temperature, guard electrode temperature, voltage and leakage current in text log files. The files may be loaded into other programs, ex. MATLAB, for post-processing.

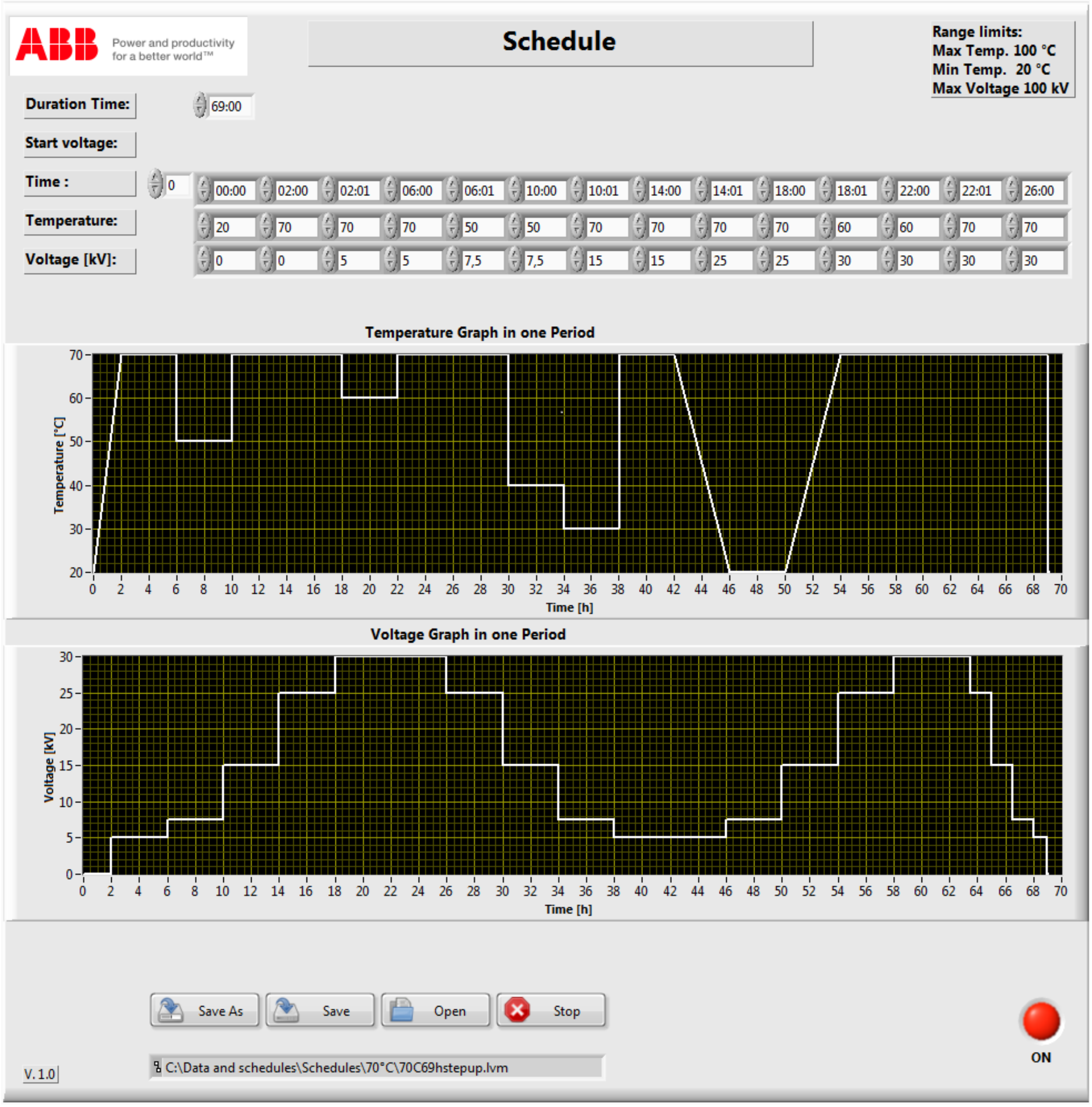
The control program also takes safety into account and turns off the heat and voltage in case of fire hazard.

3.2.1 Schedule

The Figure 3.7 shows front page of the schedule program that was made in Labview for this project. The figure also shows an example of a schedule that is possible to do for both temperature and voltage. Using this program, one can make test programs consisting of different temperatures and/or voltage levels. In this way, it is possible to perform conductivity measurements during thermal or voltage dynamics. This also allows the creation of any kind of scenario within the limits of the setup.

The program automatically limits the parameters in the schedule.

- Temperature range: $20 \leq T \leq 100$ °C
- Voltage range: $0 \leq U \leq 100\ kV$



Schedule

Range limits:
Max Temp. 100 °C
Min Temp. 20 °C
Max Voltage 100 kV

Duration Time: 69:00

Start voltage:

Time :	0	00:00	02:00	02:01	06:00	06:01	10:00	10:01	14:00	14:01	18:00	18:01	22:00	22:01	26:00
Temperature:		20	70	70	70	50	50	70	70	70	70	60	60	70	70
Voltage [kV]:		0	0	5	5	7,5	7,5	15	15	25	25	30	30	30	30

C:\Data and schedules\Schedules\70°C\70C69hstepup.lvm

V. 1.0

Figure 3.7: The schedule program for conductivity measurement.

Input parameters to be entered into the program:

- Duration time – how long the program shall do measurements
- Time – When the program shall do changes during the measurements
- Temperature – Set the oven temperature and be able to change it during the measurements
- Voltage – Set voltage on the high-voltage generator and be able to change it during the measurements

3.2.2 Control program

The main requirement for the second program was that the control and measurement is made in the same program and not two separate codes. Besides, the program should turn off the equipment in case a problem occurs, for example a breakdown or fire.

This program loads a preprogramed schedule, control the oven temperature and the voltage according to the schedule and at the same time log the measured leakage current. The program saves the oven temperature, electrode temperature, voltage and leakage current in text log files.

The files may be loaded into other programs, ex. MATLAB, for detail analysis.

The first thing that happens is that picoammeter is tested and does a test reading, the oven is put in remote and high-voltage generator is also set to remote. Default settings are set to the oven whereas the fan speed is set to 100% this is to get a homogeneous distribution of the temperature inside the oven. For security reasons, the high-voltage source is set default to zero voltage.

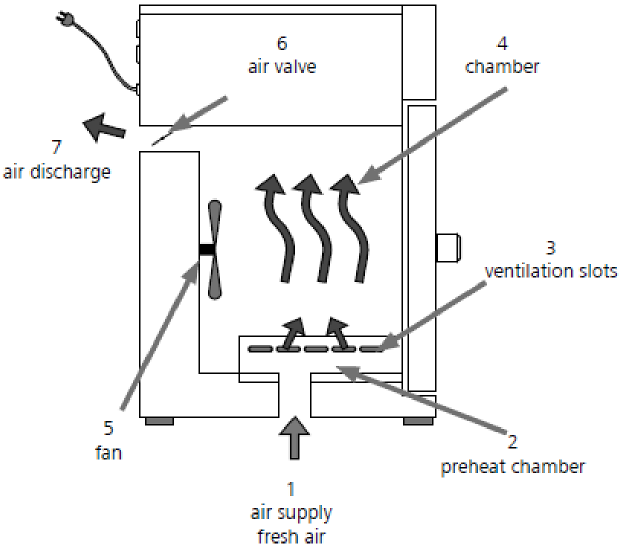


Figure 3.8: Functionality of the oven, figure from instruction manual of the Memmert oven [54]

Figure 3.8 shows the functionality of the oven. The oven temperature reaches the required temperature within 20-25 minutes but the electrode temperature takes much longer time to heat up. It is possible to solve the problem by setting the oven to higher temperature than the desired final temperature. In this way the electrode will be heated faster. When the electrode temperature approached the desired temperature, the oven setting was decreased. In this way both oven and the electrode will reach the same temperature.

Several tests were performed to find out what temperature the oven should turn off the heating and go against desired temperature. It is also desired to avoid an overshoot of the electrode temperature which is seen in Figure 3.9. Ovens temperature is not of importance in this case only the electrode temperature. But as this test shows it takes over 2 hours to reach 70 °C on the electrodes which is not acceptable to start the measurement. The final test to reach 70 °C was within 90 minutes and stable on 100 minutes which is acceptable to start the measurement for the leakage current. Because it is only possible to control one parameter in the PID controller of the oven which is in this case the temperature, one is forced to proceed in this way and still have control of the electrode temperature. If there is an overshoot one can expect to acquire an undershoot as well before the temperature stabilizes itself on the desired temperature. This is something one wants to avoid as it will take longer time before the measurement can start. This was one of the more difficult codes to write in Labview that were made for controlling the equipment in the setup.

Figure 3.9 shows the final control program made in Labview whereas it shows the graphical readings during the measurement. The first graphs show the current readings and the graph below shows the temperature readings. The two graphs to the right show the schedule for the voltage and temperature where a cursor shows where in the schedule the program is and at which amplitude.

The Labview program can also show numerical readings and status on the equipment by going to the status page.

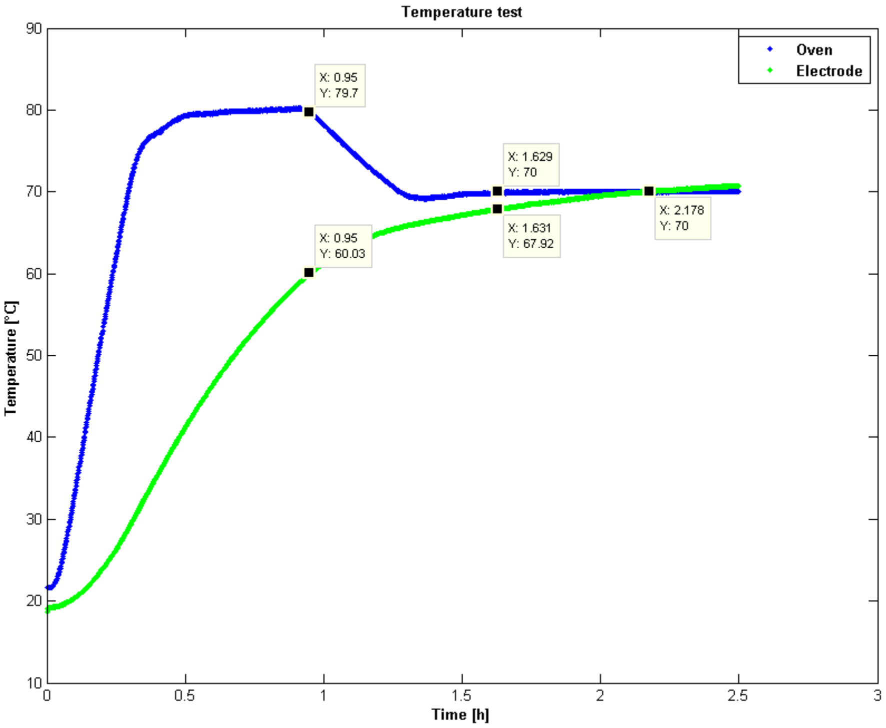
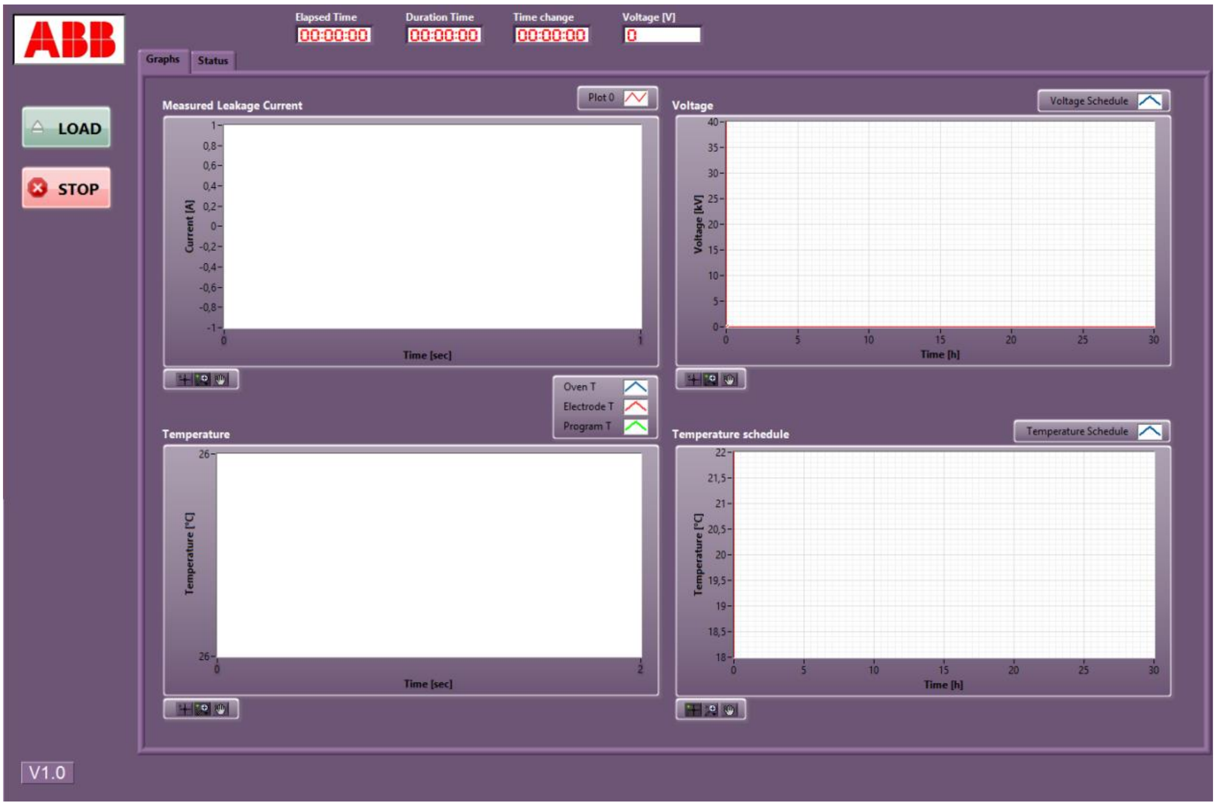


Figure 3.9: Oven vs electrode temperature



Elapsed Time 00:00:00
Duration Time 00:00:00
Time change 00:00:00
Voltage [V] 0

Figure 3.10: Control program running

4. Preparing and programs

In this work, HVDC grade XLPE material was used to produce plaque samples.

As shown in Figure 4.1 a Schwabenthan Polystat 300S press was used to produce plaque samples. There are two plates for pressing the material, one is used for melting the material and the other is used for pressing cross linking the material under a high pressure.

Figure 4.1: Schwabenthan Polystat 300S

The sample preparation was made similarly to the previous thesis worker David Elhammer [55]. The main difference is that larger frames were used in this work. New frames in stainless steel with of 27x27 cm were made with different thicknesses of 0.5, 1 and 2 mm. Table 1 shows the amount of material that is needed for making one sample for each thickness.

Table 1: The sample amount for the stainless steel frames

Thickness [mm]	m [g]
0.5	37
1.0	73
2.0	146

A few steps need to be performed before the pressing.

1. The appropriate amount of pellets was weighted on an Ohause GT410 scale [55].

2. The frame placed on the plate which is covered by Mylar film whereas the pellets are placed on the film. The pellets should be placed as close to the middle as possible in the form of a hill or pyramid. This is to press the air out when pressing so there is no air left to create voids in the specimen. This is very important because it can affect both the conductivity and be the cause of a breakdown during the measurement.

Figure 4.2: Mylar film covers the frame and the pellets gathered in the middle

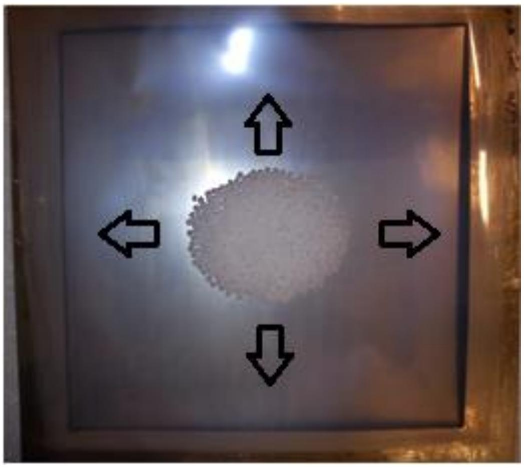


Figure 4.3: When the press is pressing shall it move the mould out in all directions whereas it also presses the air out to prevent voids

3. A second film is placed to cover the pellets. Then, the second plate is placed above. This sandwich is put between the lower plates to melt the pellets with a pressure of 40 bar at a temperature of 135 °C for 4 minutes. After the four minutes, the pressure is increased to 340 bar for 2 minutes. Hence, 6 min at 135 °C in total.

4. The sandwich changes place from the lower plate on the press to the upper plate. Here the pressure will still be at 340 bar but with a temperature of 185 °C for 12 minutes. Pellets crosslinks around 180 °C, but because of the heat distribution is 185 °C used.

5. After 12 minutes, it is time to cool down process which is made manually on the press and wait until it reaches around 30 °C which takes around 6-8 minutes.

6. The sample is taken out and the frame is removed.

The press program is shown in Table 2.

Table 2: Program step used in the thesis for pressing

Step 1 melt the material					Step 2 crosslink the material		
T_1 [°C]	P_1 [bar]	t_1 [min]	P_2 [bar]	t_2 [min]	T_2 [°C]	P_3 [bar]	t_3 [min]
135	40	4	340	2	185	340	12

4.1 Important considerations prior and after conductivity measurement

If the specimen is not degassed, it is important to take the sample directly into the cell and put the sample between the electrodes. It is also important to keep the Mylar film on, because as soon as the sample comes into contact with air it is influenced by the surroundings and also begins to degas. The XLPE material should be kept sealed so that it does not come into contact with air otherwise the chemicals such as antioxidants can leave the material and its properties change. It is also important to keep the XLPE material away from sunlight as it is very sensitive to the sunlight. In sunlight, it becomes more yellow in colour and the material properties can change.

The pressed sample should be wrapped in Aluminium foil or other diffusion barriers to prevent cross linking by products and other chemicals diffusing out of the sample. The measurement should be made immediately, or else, the sample should be kept in a freezer to avoid changes in its chemical and physical composition. In this study, all measurements were made on freshly pressed samples.

After the measurements the samples were wrapped in Aluminium foil and directly put into a freezer. The reason to freeze the sample is for residual gas analysis to find out if there are any residual gases remaining in the sample. The residual gases were later measured to evaluate the amount of degassing which occurs during the measurements.

If the sample should be frozen down or be kept in room temperature, it is also important to cover the sample with aluminium foil when the foil protects the sample from being influenced. For very thin specimens, there are no residuals left as they have been totally degased during the measurement. This is one of the reasons why the thick sample is of greater interest that there are residual gases remaining in the specimen.

The electrodes were cleaned with ethanol each time the samples were changed.

5. Results and Discussion

The results of all measurements are presented in this section as the testing of the conductivity cell, measurements made with different parameters and conditions.

To find the accuracy of the measurement setup and finding a useful test program, measurements were made on 0.5 mm thick pressed XLPE plaques.

Measurements were made with electric fields from 10 to 60 kV/mm at temperatures from 25 °C up to 70 °C. Due to these tests, it can take a day or several days to perform tests for 24, 48 and for 72 hours.

5.1 Testing the cell

During the first four tests a 50 Hz interference was observed which influenced the measurements. The measured noise is at level of 40-50 nA. Because of the noise it is hard to analyse the leakage current more than that repeatability is good. After fixing the error in the connections, the noise level decreased down to the range of 1 nA.

To check the repeatability of the measurement, the measurements with three freshly pressed samples were performed at 70 °C and 15 kV. The voltage was applied after the samples had reached the stable temperature. The result is shown in Figure 5.1. The first measurement took 3 days and the other two measurements around 23 hours. The results clearly show a very good repeatability in the results. The results converged to similar levels.

It is possible to reduce the noise by performing digital filtering on the data. This is done using moving average or moving median in Matlab which Figure 5.2 shows.

During the first minute, the polarisation current dominates. The main observation is that the current does not seem to stabilise even after three days of testing and it continues to decrease. This is because the conductivity of the material decreases with time.

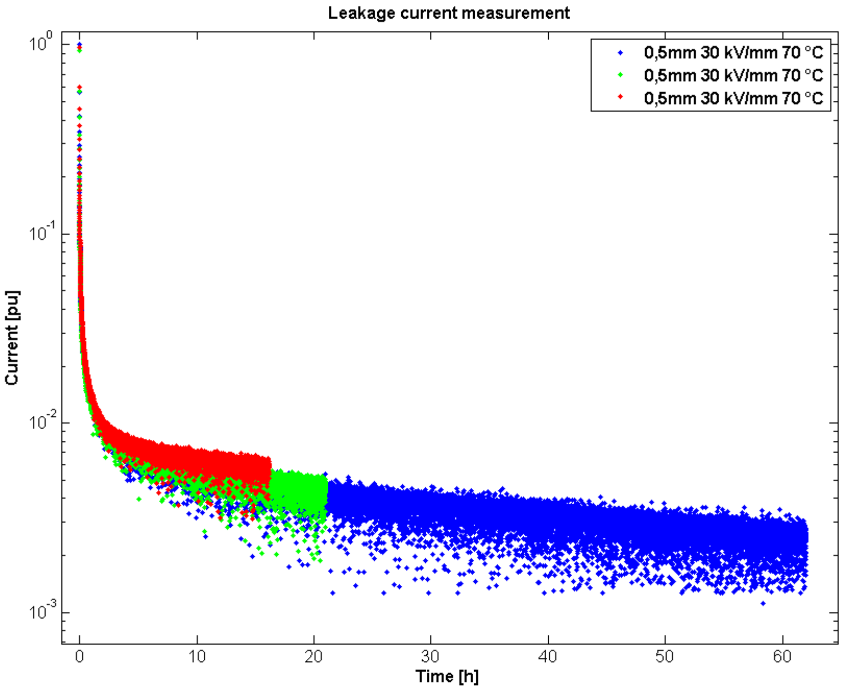


Figure 5.1: Leakage current plotted in semi logarithmic without filter. Data: h = 0.5 mm, U = 15 kV, T = 70 °C

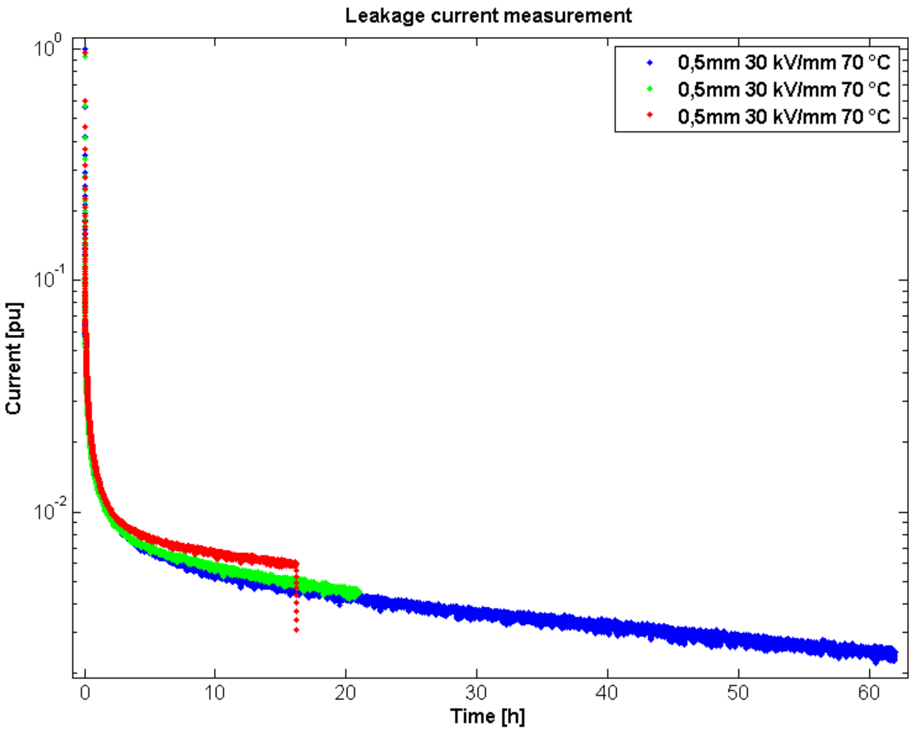


Figure 5.2: Leakage current plotted in semi logarithmic with filter, Data: h = 0.5 mm, U = 15 kV, T = 70 °C.

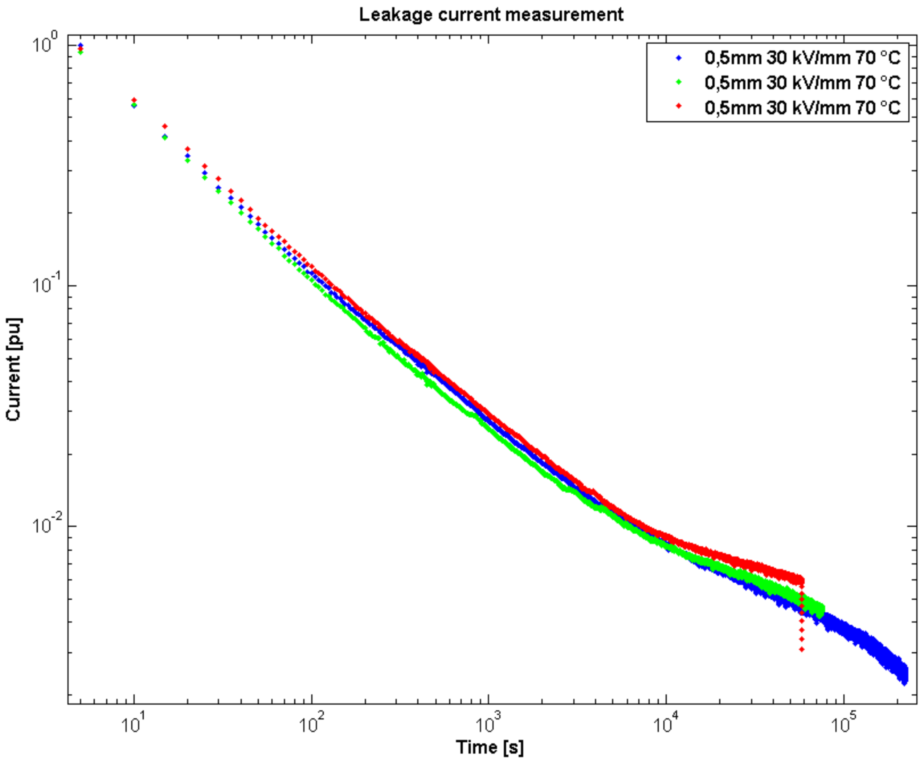


Figure 5.3: Leakage current plotted in logarithmic, Data: h = 0.5 mm, U = 15 kV, T = 70 °C.

The first two figures show that it is good repeatability and that the curves are uniform. By plotting the curves in logarithmic scale, provides more information about the curves, which is seen in Figure 5.3. By looking at the measurement in logarithmic scale, it can be clearly seen that the curve has a slope of -0.5, which is good when it is consistent with measurements in other articles and literature. In literature, there is normally a change of slope however as observed there is almost no change of slope just continuous to go down in a straight line. There is a small change of direction in the slope around 10^4 seconds, however, not as great other studies show.

5.2 Round robin measurements

After building such a measurement setup, it is very important to make sure that the measurement system works properly. This may be done by comparing the measurement results with already existing similar setups. Therefore a round robin study was performed similar to the one that ABB CRC and Borealis in Stenungsund, see reference [6]. The round robin was executed in three different locations ABB HVC Karlskrona, ABB CRC Västerås and at Borealis in Stenungsund. 12 similar 1 mm thick plaque samples with HVDC grade XLPE were produced at Borealis were used in the measurements. Beside the leakage current measurement, residual gas analysis was also made for each sample.

The measurements were performed in four days with the program to replace the samples after 24 hours. The samples were heated up to 70°C and when they reached stable temperature, 30 kV was applied and the leakage current was measured for approximately 23 hours.

The round robin test was performed on another XLPE material and with a different thickness. This is for checking the repeatability of the cell. The result is shown in Figure 5.4. There was a good agreement between the measurements from all three locations. The results presented here are only from ABB HVC.

The first observation is that we observed a good repeatability of the measurements here as well. As in the previous measurement, there is a slope of -0.5 which is expected, see Figure 5.5.

Comparing the measurements in Figure 5.5 and Figure 5.3, they are seen to be very similar. The small difference is that the round robin measurement goes strictly down and is continuous with no slope of change as the test measurement shows.

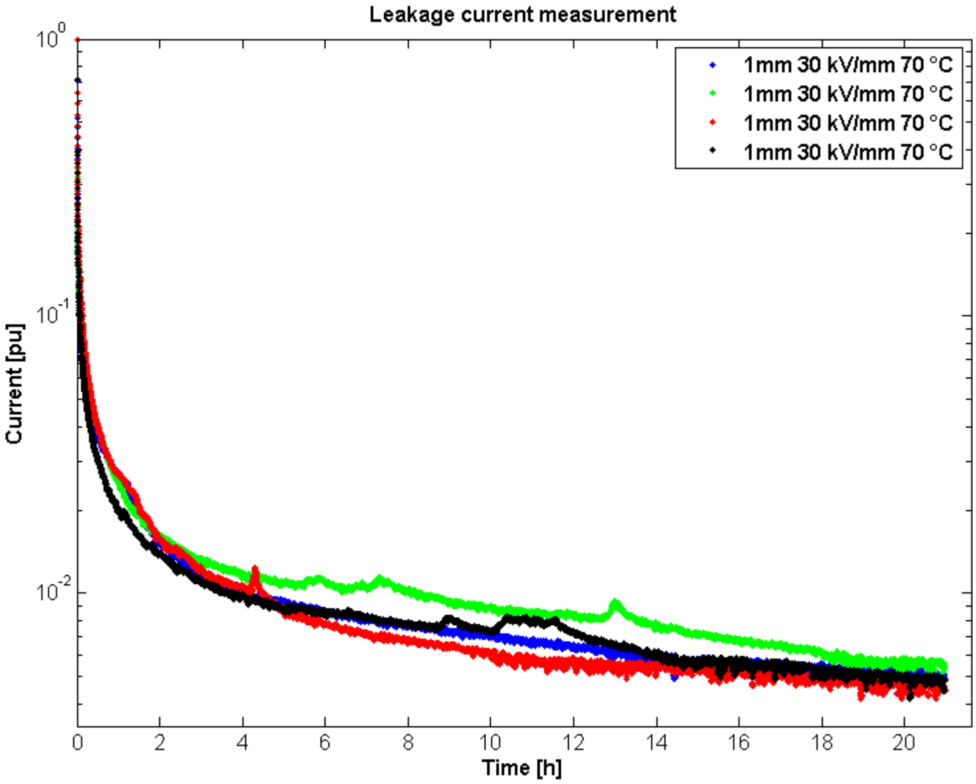


Figure 5.4: Round robin measurement in semi logarithmic plot, Data: h = 1 mm, U = 30 kV, T = 70 °C.

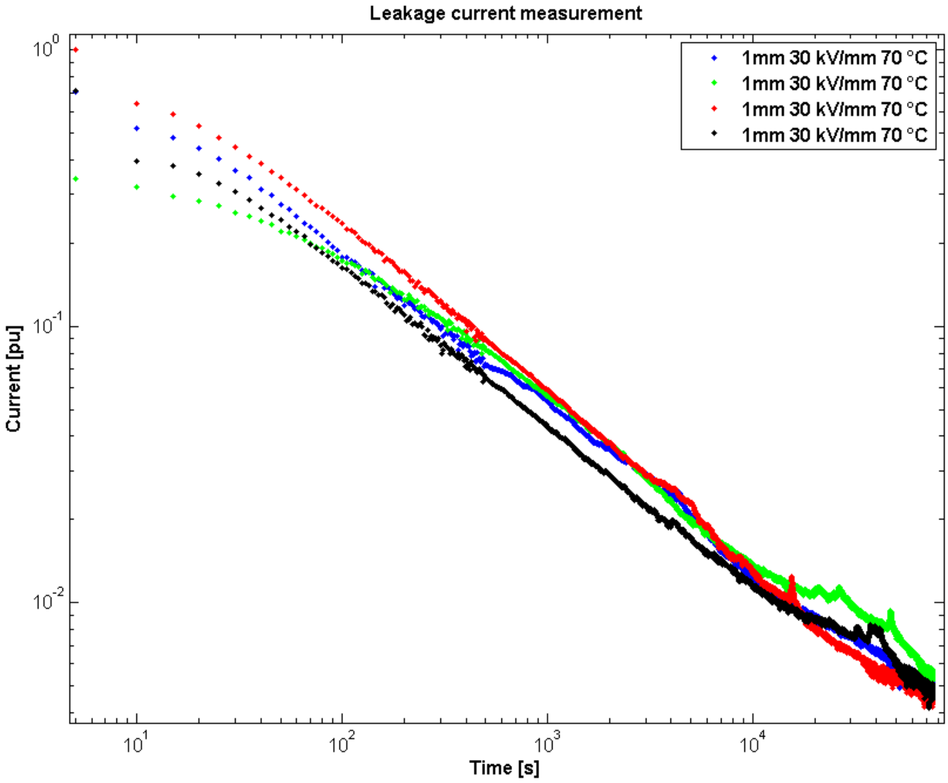


Figure 5.5: Round robin measurement in logarithmic plot, Data: h = 0.5 mm, U = 30 kV, T = 70 °C

5.3 Leakage current measurements with different parameters

Figure 5.6-Figure 5.9 shows the leakage current for 10 kV/mm for two different temperatures of 25 °C and 70 °C. The curve in Figure 5.6 works its way up after the high-voltage has been switched on. It has the same behaviour as the previous measurement: after 10^4 seconds, the slope changes slightly. This curve is hard to analyse because it contains a lot of noise.

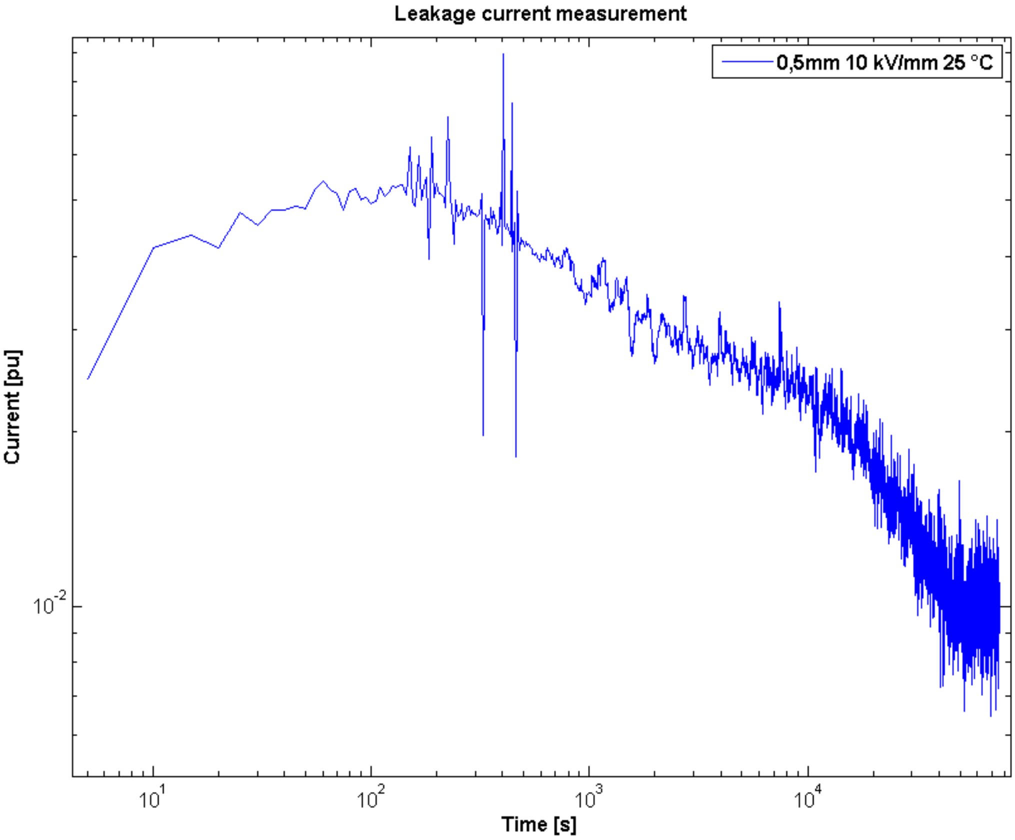


Figure 5.6: Leakage current measurement logarithmic plot at room temperature. Data: h = 0.5 mm, U = 5 kV, T = 25 °C.

The next measurement at 70 °C is shown in Figure 5.7 which is almost a straight line in the log-log plot with a slope of -0,5 from start to end. It decreases even after 10^4 seconds. One can observe that the measurement has much less measurement noise comparing to the room temperature measurement. It also has less disturbances compared to previous measurements at 30kV/mm for the same temperature.

Figure 5.8 shows both curves in the same plot. Here, it is clearly visible that at 70 °C, the leakage current decreases faster and that the leakage current does not contain any noise at all in comparison to leakage current in room temperature. Furthermore, it can be observed that both curves have a directional change at 10^4 seconds which is hardly noticeable for 70 °C. Figure 5.9, plotted in semi-log shows that at 70 °C the leakage current curve is uniform and stable in comparison to the room temperature leakage current. This may be due to the fact that at room temperature, the temperature has little influence on the specimen. The specimen is mainly affected by the electric field. While at 70 °C, both temperate and electric field influence the specimen.

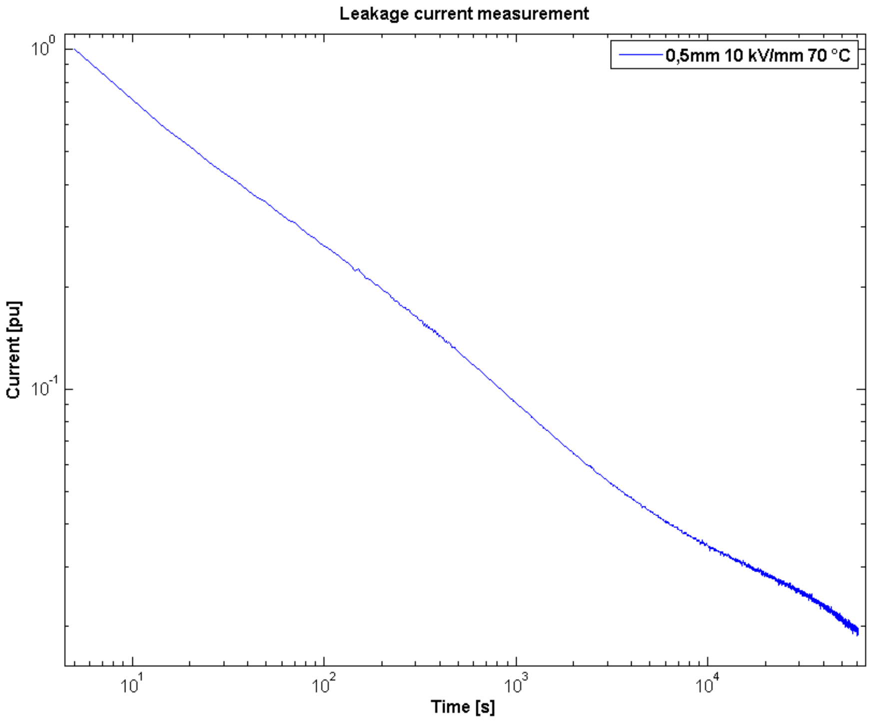


Figure 5.7: Leakage current measurement logarithmic plot at 70 °C. Data: h = 0.5 mm, U = 5 kV, T = 70 °C.

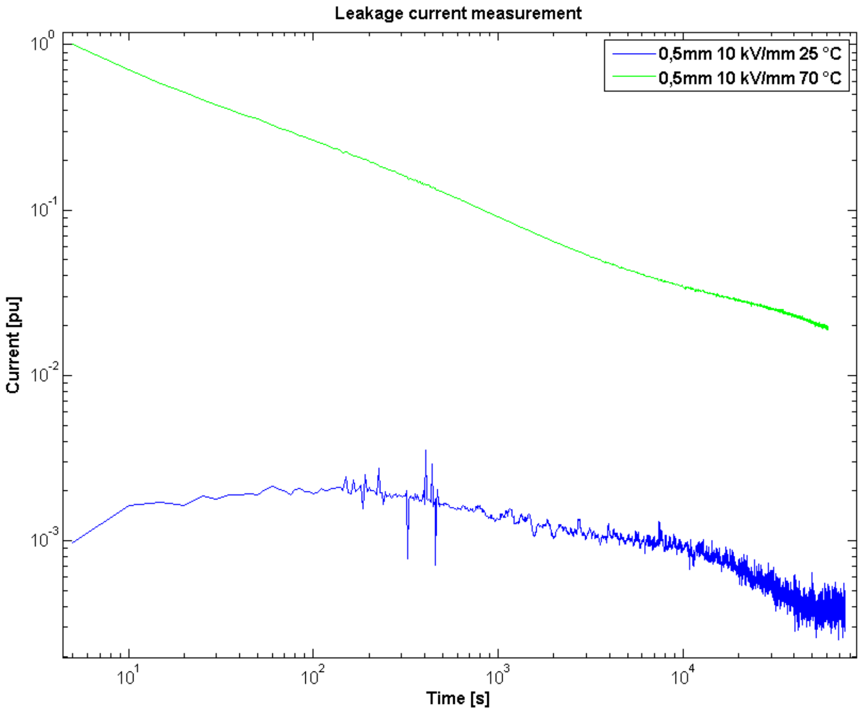


Figure 5.8: Leakage current measurements in logarithmic plot at 10 kV/mm for the temperatures of 25 °C and 70 °C

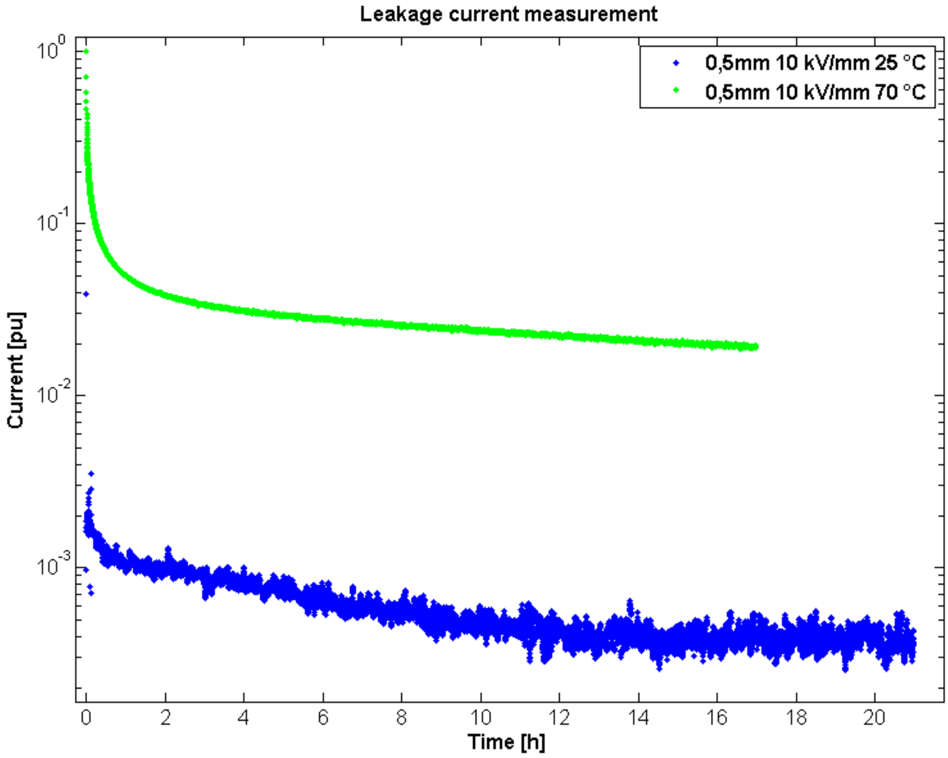


Figure 5.9: Semi logarithmic plot. Measurements at 10 kV/mm for both 25 °C and 70 °C.

5.4 New tests

The next two experiments are something that have never before been published. So there are no expectations on what the results will show. The first experiment is about polarisation and the second will be about temperature cycling. The reason for these tests was to investigate what happens when changing a parameter or conditions during the measurement.

5.4.1 Polarisation test

The polarisation experiment was to investigate the behaviour of the leakage current when turning the HV source on and off. Because the Spellman HV source only has positive polarity, the depolarisation cannot be simulated and therefore the discharge that appears in the measurement will come from the HV capacitor with some additional low measurement noise. The result from the experiment is shown in Figure 5.10.

The measurement was for 69 hours at a temperature of 70 °C where the voltage first was turned on for three hours and off three hours. The length between each interval for turning on and off increased with 3 hours: 3-3, 6-6, 9-9, 12-12 and 9.

The first impression of the measurement is that it clearly observes the polarisation every time the high-voltage generator is switched on during the measurement. The depolarisation current is not measured. The leakage current behaves as previous measurements: it strictly decreases. Very interesting is the behaviour of the polarisation every time the voltage is turned on. The polarisation current tends to the same conductivity current in the curve where it should have been if the voltage never was turned off.

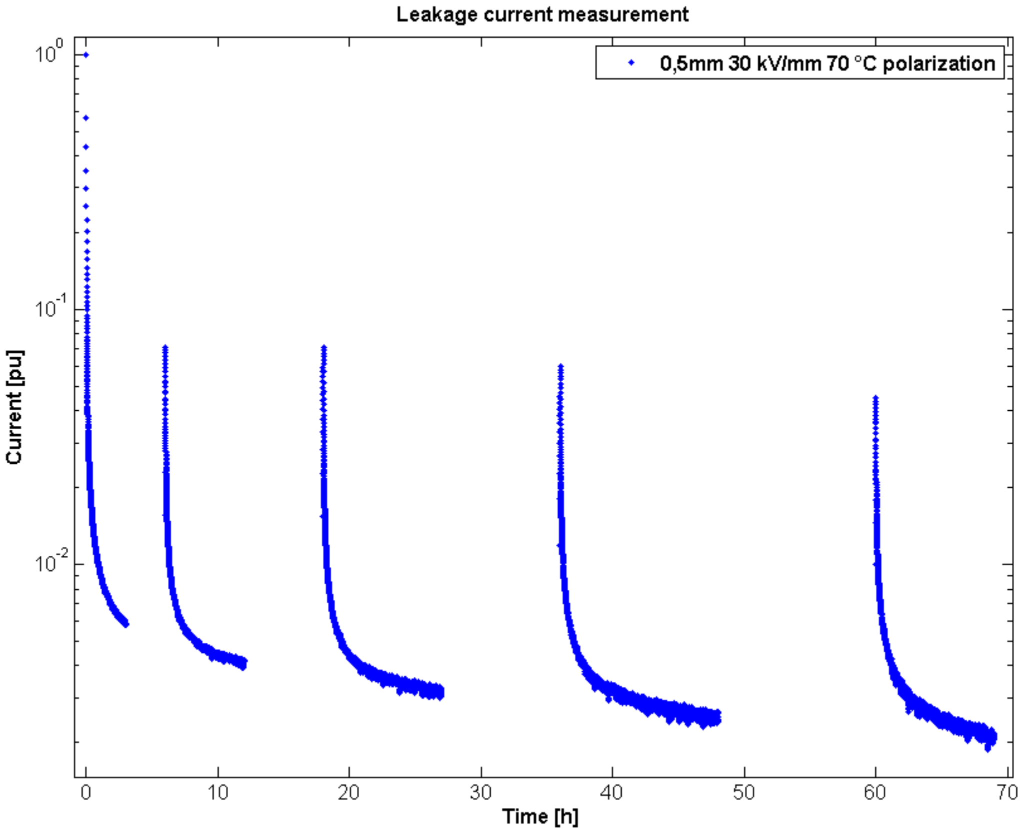


Figure 5.10: Polarisation experiment, semi logarithmic plot. Data: h = 0.5 mm, U_{on} = 15 kV, U_{off} = 0 V, T = 70 °C.

The electric field doesn’t seem to affect the evolution of the conductivity. The conclusion of the measurement is that only the temperature is affecting the measurement over time at 70 °C.

5.4.2 Temperature cycling experiment

A cycle experiment was performed to investigate the behaviour of leakage current if temperature changes over a longer period of time for 72 hours with a constant voltage.

The temperature should first go from 20 °C to 70 °C on 1.5 hour to then remain at 70 °C in 2.5 hours. After that, the temperature should decrease to 20 °C within 8 hours and then repeat the same cycle again. A full cycle takes 12 hours.

The HV is on from the start to the end during the measurement at 5 kV.

The result is visible in Figure 5.11-Figure 5.13. Figure 5.11 shows the measurement in linear scale. The most interesting result was how the leakage current follows the temperature. First, the leakage current rises with temperature, and then goes down when the temperature goes down to 20 °C. This is plotted in semi-log y scale in Figure 5.12 and in log-log scale in Figure 5.13.

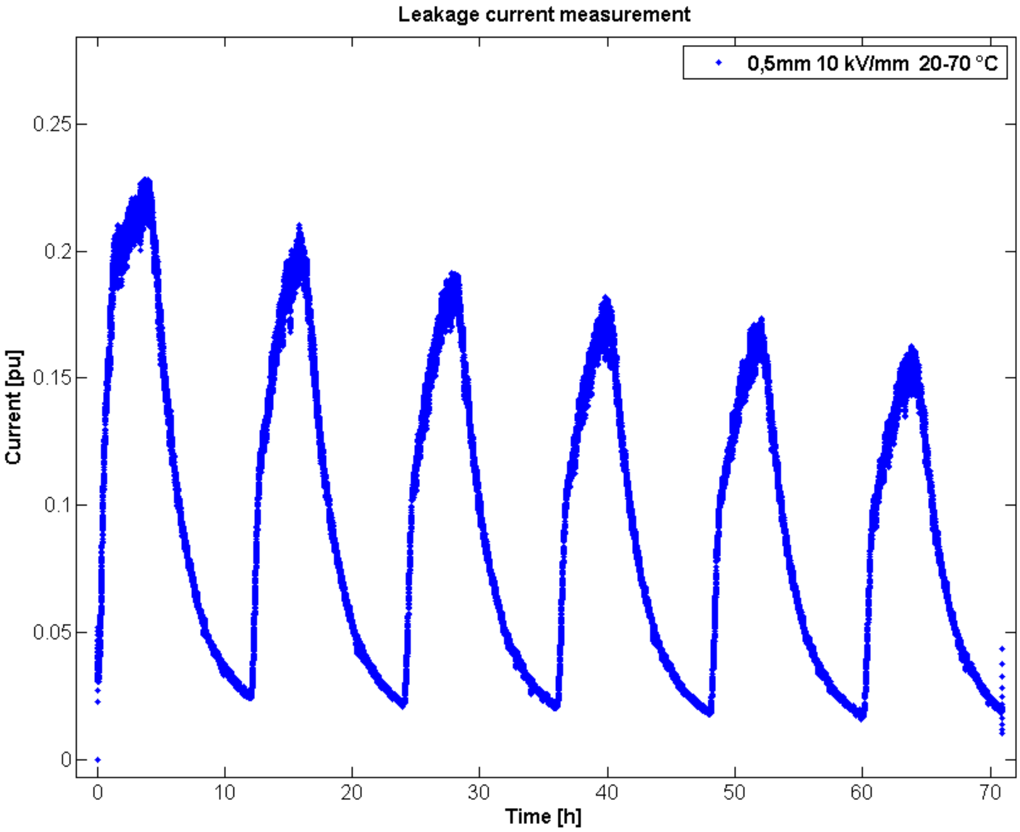


Figure 5.11: Measurement in linear plot for thermal cycling between 20-70 °C and 10 kV/mm.

In Figure 5.11 and Figure 5.12, the same behaviour is observed for both plots where one can clearly see how the current increases with the rising temperature and then decreases when the temperature drops. This behaviour is repeated for each cycle; the leakage current decreases for each cycle and the longer the measurement is in progress.

Figure 5.14 shows how the temperature has behaved for both the electrode and oven. It is interesting to see how the electrodes the temperature follow the ovens temperature fairly well. However, neither the oven nor the electrode reach down to 20 °C. The oven gets down to around 30 °C, while the electrode is around 33 °C before it turns again for the next cycle. This means that if we want to go down to 20 °C, we need to go down in temperature for a longer time as 8 hours is not enough, see Figure 5.14.

The way the leakage current follows the temperature as shown in Figure 5.11 and Figure 5.12 is interesting. By looking at the peaks one can see how the current slowly goes down in the specimen over time for each cycle which is seen in both figures.

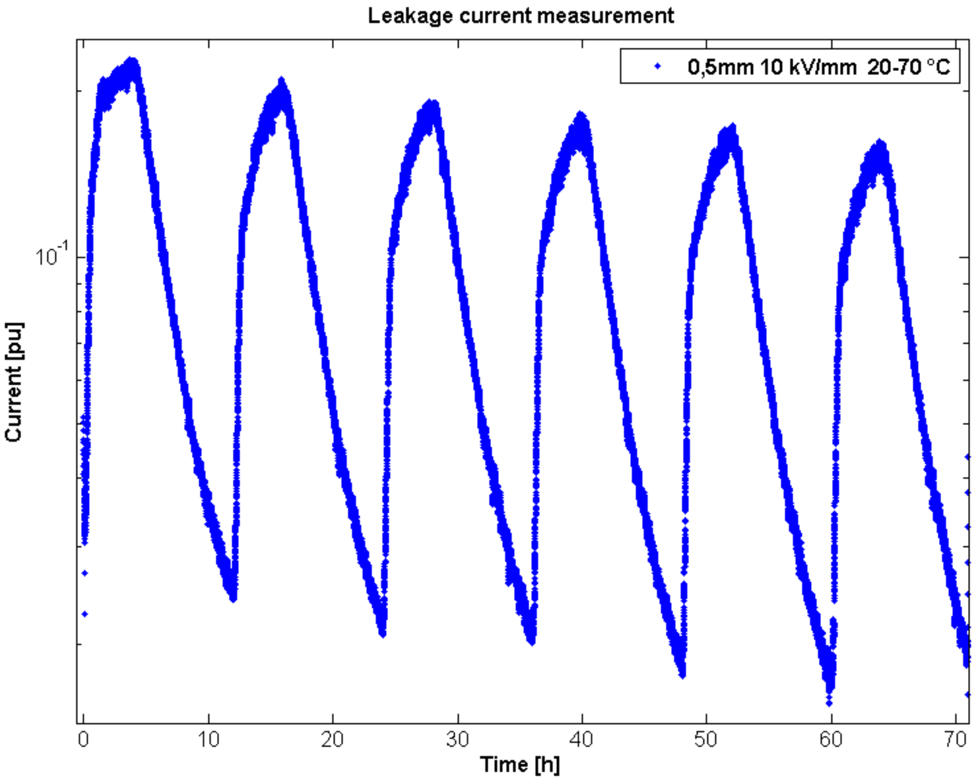


Figure 5.12: Semi logarithmic plot for thermal cycling between 20-70 °C and 10 kV/mm

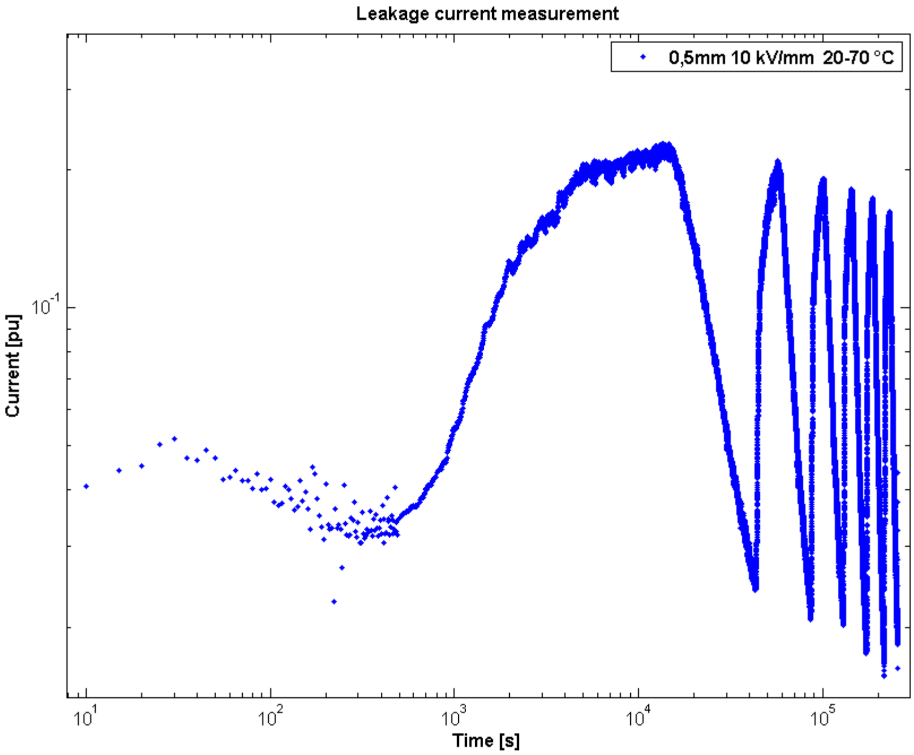


Figure 5.13: The cycle test in logarithmic plot, 20-70-20 °C and 10 kV/mm.

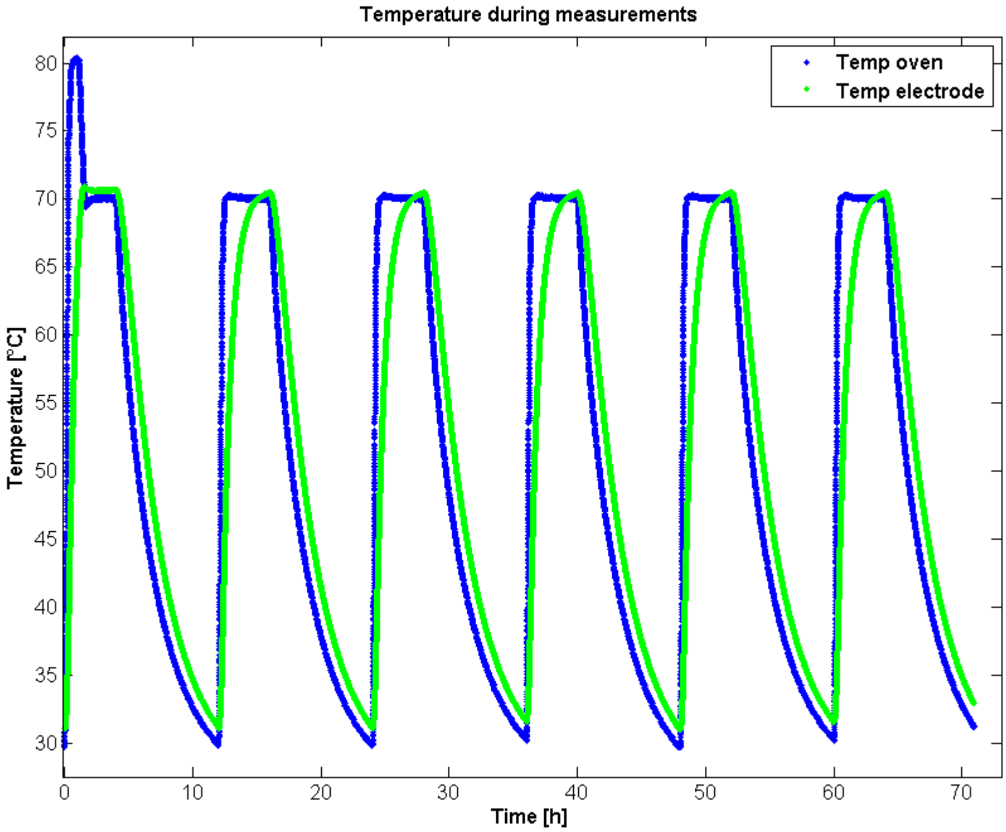


Figure 5.14: Temperature behaviour for the cycle test, oven vs electrode

6. Conclusions

The first main objective of the project was to manufacture a test cell to perform repeatable and reasonable measurements of the electrical conductivity of thick insulating plate samples. The second objective was to investigate the validity of the measurement techniques when changing the conditions or parameters of the measurement, such as temperature and voltage. This measurement setup is still new and there are not many published articles for comparison of results. Because there are not so many articles to compare results with [5], [6], [18], [50], other methods are required to validate the results. These references are a good comparison for the measurements [12], [34] and [35]. The conclusion is that the conductivity cell is working correctly, the measurements are repeatable and results are reasonable. This was the main task of the project.

The most important feature of the test cell is the control of the conditions. This is a cumbersome task in many setups. In the laboratory of the performed measurements, it is possible to control both the temperature and voltage during the measurements. In many laboratories, it is only possible to set one temperature and voltage manually. With the Labview program for controlling the cell, it is possible to create any kind of scenario. However, the limitation of the setup is the high-voltage and it is only possible to go up to 45 kV.

One can never exactly obtain the same results when measuring leakage current as each new specimen itself is unique. This is the case even when following the same procedure every time when pressing the plaque sample and is clearly visible in the result in the graphs. Because the samples are fresh and not degassed, it is important to place the specimen between the electrodes as quickly as possible. Another conclusion from the measurements, which also is visible in the plots, is that the results depend on the initial temperature of the oven. The initial temperature will become a source of error that should be noted before measurements as it will affect the measurements shown in Figure 5.1-Figure 5.7. The magnitude of the leakage current/conductivity measurements will depend on how long the specimen has been exposed to the temperature before the measurement starts. This effect is visible in Figure 5.1-Figure 5.7.

Another source of error to the measurements is that the material is sensitive to exposure to air. Every time the bag is opened, the material is exposed to ambient air and the chemicals can escape the material and this affects the conductivity.

The measurements are very sensitive to both the temperature and electric field. Comparing the tests applying 10 kV/mm at room temperature and at 70 °C, the effect of temperature dependence is clearly seen. In the case of room temperature, the specimen is only dependent on electric field, which displays a lot more interference, while at 70 °C the specimen is also temperature dependent. Looking at the polarisation test, no effect of the electric field at 70 °C can be seen, the leakage current is constant. This means that the case of situation or parameters that is used for a certain case will affect the measurement. This raises another large question: when does the temperature become dominant? This is something to think about for future research and testing.

The conclusion for room temperature tests is that the conductivity does not decrease as it does at higher temperatures. The assumption and hypothesis of this is because there is no temperature that is affecting the specimen which is only dependent on the electric field at room temperature.

With aid of the peaks in the cycling experiment, the conclusion can be drawn which is visible in all the measurements: the leakage current continues to go down over time, faster in the beginning and slower reduction with time. The results from the polarisation test raised the question again whether the specimen was affected by the electric field at 70 °C or only by the temperature. One of the reasons for this could be that the chemical composition of the XLPE material is changing over time with the temperature which is observed in similar measurements with other measurement setups.

With this electrode system it is possible to go up to 45 kV before flashover occurs. The protection and measurement circuit is designed for measurement of polarisation current. The depolarisation current cannot directly be measured with this protection system since it includes a parallel capacitor and a relatively large resistor. It is of course possible to adopt the setup to measure even depolarisation current but it needs some modifications.

7. Further research and improvements

For future research it would be advised to look at other thicknesses of the samples as 2 or 3 mm and at different temperatures both lower and higher than 70 °C. Another interest is to find the temperature at which the temperature dependence becomes dominant over the electric field and if the temperature differs with thickness of the specimen. More cycling tests should be performed to learn more about the behaviour of the leakage current where both the temperature and voltage are changing and not only keeping one of the parameters constant.

Improvements that can be made to the cell are to place an additional electrode inside the oven and measure two plaque samples at the same time.

Further improvements are to obtain a HV source with negative polarity or one with both polarities. If the HV source would have had with both polarities, it would be possible to investigate polarisation and depolarisation on a plaque sample. More studies should be made with a negative HV source aslo.

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