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NTNU
Norwegian University of Science and Technology

Daniel Ekornrud Fjeldstad

Condition Assessment of Generator Bars by Time Domain Dielectric Response Measurements

Master's thesis in Energy and Environmental Engineering

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Abstract

The majority of Norwegian hydropower generators have been in service for 40 or more years, meaning they are reaching the end of their expected lifetime. New operation conditions introduced in recent years makes condition assessment methods more important in order to understand the limitations and expected life of the equipment. This thesis has therefore explored dielectric response as a condition assessment method and validated a megger as potential test equipment for the method. Several service aged stator bars have been tested on different temperatures and voltages. The megger had significant problems producing credible results on lower temperatures due to the low current. The sensitivity level of the megger was found to be 1 nA. A current level in which results had noise of ± 20-30 % current variation per second. Low currents tests also had the occurrence of negative DC currents, breaking with the theory. The megger was able to detect trends in the bars for tests above 90 °C and establish the individual bars DC conductivity and dielectric loss. For these temperatures there were also found some uncertainty in the current measurements from the megger caused by a randomness in current level when measuring. The bars were also subjected to thermal cycling according to IEEE st 1310 and identical tests were repeated. Thermal cycling was found to show no significant impact on the bars. Dielectric response as a method has great potential, but needs significant amount of data handling and data from unaged test objects for comparison. A megger as test equipment does not perform satisfactory on single stator bars but needs further detailed study with repeat testing and other test objects to say for certain.

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Introduction

Most Norwegian hydropower generators have been in service for more than 40 years and can in many cases be considered as having reached their expected service lifetime. In addition, new and tougher operation conditions, including higher and more variable loads, challenge the insulation beyond what it originally was designed for. All factors which increase the need for reliable diagnostic tools and condition assessment schemes for estimating expected remaining lifetime. A study performed by CIGRE [1], found that the most common cause for deterioration on hydropower generators are insulation damage. Of which the stator is the most common component for the damages. Today, dielectric response measurements are one of several diagnostic techniques used for condition assessment. Unfortunately, wide application of this technique is hampered by rather uncertain interpretation and lack of clear assessment criteria. The main purpose of this MSc-thesis is to address these issues and to use characterization techniques available for detecting changes in dielectric response, i.e changes of conductivity and dielectric loss, of service aged stator bars. The effects of temperature and thermal cycling will be of particular interest. A megger will be used as measuring equipment and its suitability for the method will be investigated.

1 Theory

1.1 Generator stator bars

The generator stator bars is what makes up the stator coils in a generator. The conductors in the bars are individually wrapped in several layers of insulation, see Figure 1. The most common configuration is the use of mica tapes and an epoxy resin. The process of correctly insulating the bars is rather difficult, and it is unfortunately impossible. The dimensions must be perfect in order for the bars to properly fit in the slots of the stator, failing to do so may cause faster degradation due to vibrations. It is also desirable to avoid any form of wrinkles when applying the tape, or failing to evenly distribute the resin, as this can create voids leading to field enhancement which carries a partial discharge risk [2].

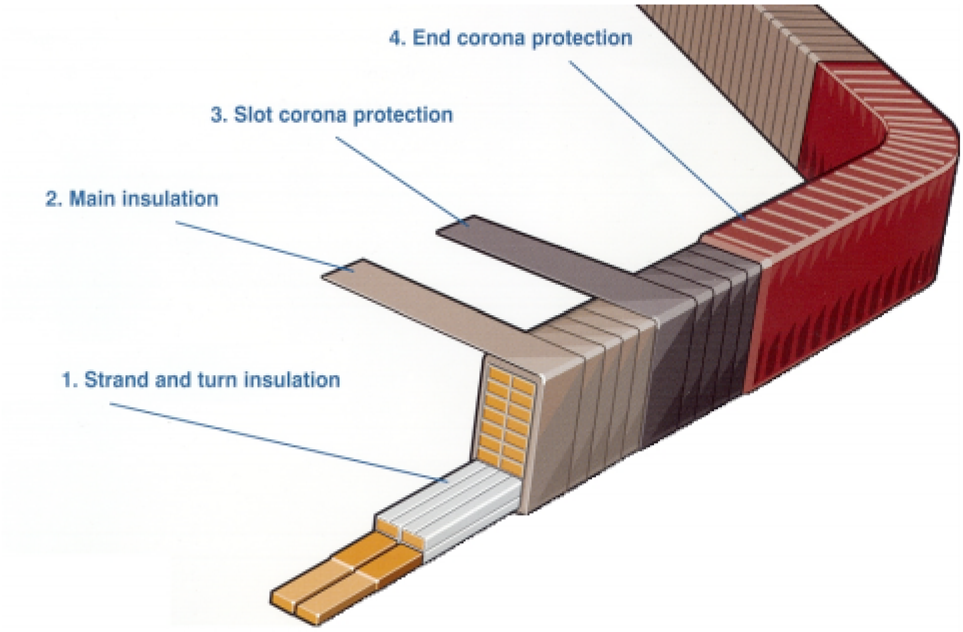


Figure 1: Cross section of a stator bar showing the different layers of insulation around the conductors [2]. In this thesis it is the main insulation which will be tested.

It is impossible to prevent the inevitable degradation of the insulation system due to the different stresses it will experience during normal operation. It is common to divide the stresses in the four categories of electrical, mechanical, thermal and environmental stresses. The stresses creates aging mechanisms, which accelerates the degradation until a breakdown occurs. Overloading and more frequent starts and stops becomes more common with the ever increasing demand for electricity and have been showed to significantly increase the deterioration of the insulation. Implementing proper condition monitoring will allow for the correct maintenance strategies, which can reduce this rate of degradation. It will also allow for a more clear understanding of the equipment's limitations, and preferably prevent or reduce operations to that limit [3].

1.2 Polarization

The material used for insulation in generator bars are called a dielectric. Polarization occur when a dielectric is exposed to an electric field. Without a field, the dielectric material consists of bounded electric charges with random orientation. When a field is applied, the dipoles will start aligning with the fields direction. This polarization, P, adds to the vacuum displacement density D as shown in [4], [5]:

$$D = \epsilon_0 \cdot E + P = \epsilon_0 E + \epsilon_0 \chi E \tag{1}$$

The displacement factor $D = \epsilon_r \epsilon_0 E$ and the dielectric susceptibility is given $\chi = \epsilon_r - 1$. Where E is the electric field, ϵ_r is relative permittivity and ϵ_0 is the vacuum permittivity. The expression for polarization is then given:

$$P = \epsilon_0 E(\epsilon_r - 1) \tag{2}$$

There are mainly four types of mechanisms causing polarization [5]:

- *"Electron polarization: displacement of negative electron shell relative to the positive nucleus".*
- *"Ionic polarization: displacement of ions in a molecule with different polarity against each other"*
- *"Orientation polarization: orientation of polar molecules, molecule groups or particles"*
- *"Interfacial polarization: accumulation of charge carriers at macroscopic or microscopic interfaces between materials with different conductivity"*

The different polarization mechanisms have different time constants and polarization is severely time dependent. The two first mechanisms are considered momentary, meaning they can follow the change in electric field and align instantaneously with it. The latter two mechanisms are known as relaxation mechanisms and are slow processes [4], [5]. It is these slow mechanisms that may cause the losses discussed in subsection 1.4.

The equivalent circuit of a dielectric material is shown in Figure 2

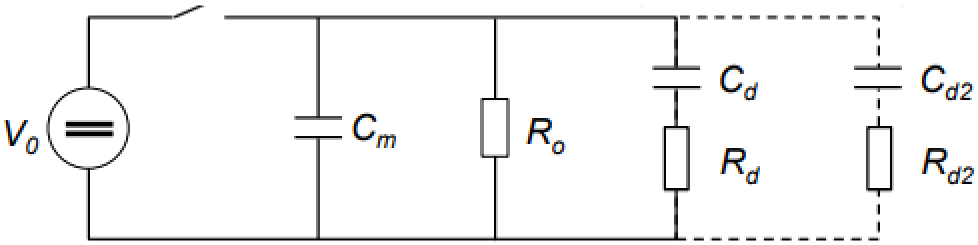


Figure 2: Equivalent circuit of a dielectric material. The different components represents the polarization mechanisms [4].

When a voltage V_0 is applied, a current will flow trough the circuit. The components represents the behavior of the dielectric when the voltage is applied. C_m represents the momentary (quick) polarization mechanisms. R_0 represents the DC conductivity in the material, while the RC series parts at the end represents the relaxation mechanisms. As there is possible for a dielectric to have several relaxation mechanisms, depending on the material, more RC series can be connected in parallel at the end of the equivalent circuit.

1.3 Time domain dielectric response

Measuring the dielectric response in the time domain is conducted by subjecting the test object to a high DC voltage. The most common method of analysis is to study the polarization (charging or absorption) and depolarization (discharging or reabsorption) currents. The schematic for testing is showed in Figure 3. First the test object is charged for a set time. Usually between 10-30 minutes is needed to achieve full absorption [6]. This is occurring while the switch is in position 1, after which the test object is grounded by placing the switch in position 2 leading the object to start discharging.

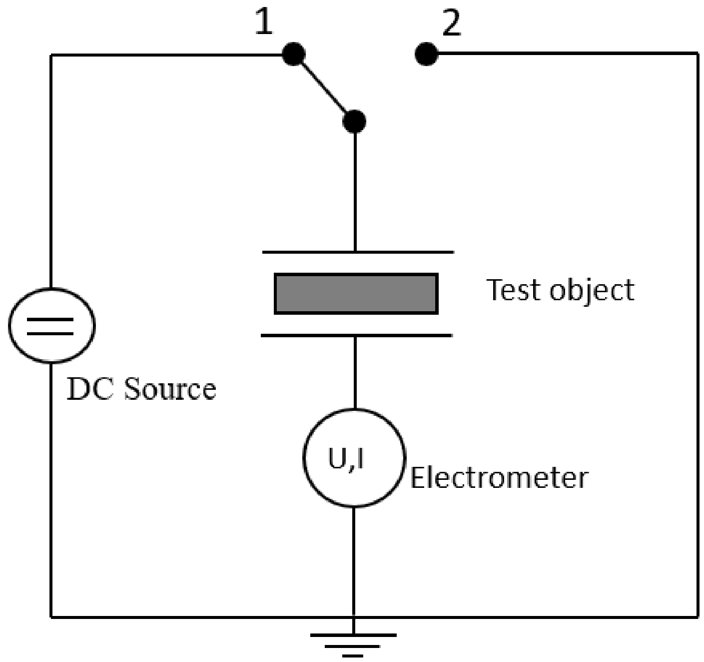


Figure 3: Schematic showing the measurement setup in time domain [7].

From the literature, [2] [8] [9], the polarization current is commonly written as:

$$I_{pol}(t) = C_0 U_c \left[\frac{\sigma_0}{\epsilon_0} + \epsilon_\infty \delta(t) + f(t) \right] \tag{3}$$

Where

- C_0 = geometric capacitance ≈ measured capacitance of object
- U_C = the amplitude of the step voltage
- σ_0 = DC conductivity of the dielectric material
- ϵ_0 = permittivity of vacuum
- ϵ_∞ = high frequency component of the permittivity
- $\delta(t)$ = the delta function due to the sudden step voltage
- $f(t)$ = the response function of the dielectric material, dependent on the polarization mechanisms in the material.

After the short circuiting the test object, the depolarization current can be written as:

$$I_{depol}(t) = -C_0 U_c \left[\epsilon_\infty + f(t) - f(t+t_c)\right] \tag{4}$$

Where Figure 4 shows typical waveforms for both currents and the contributions from the different terms in the expressions.

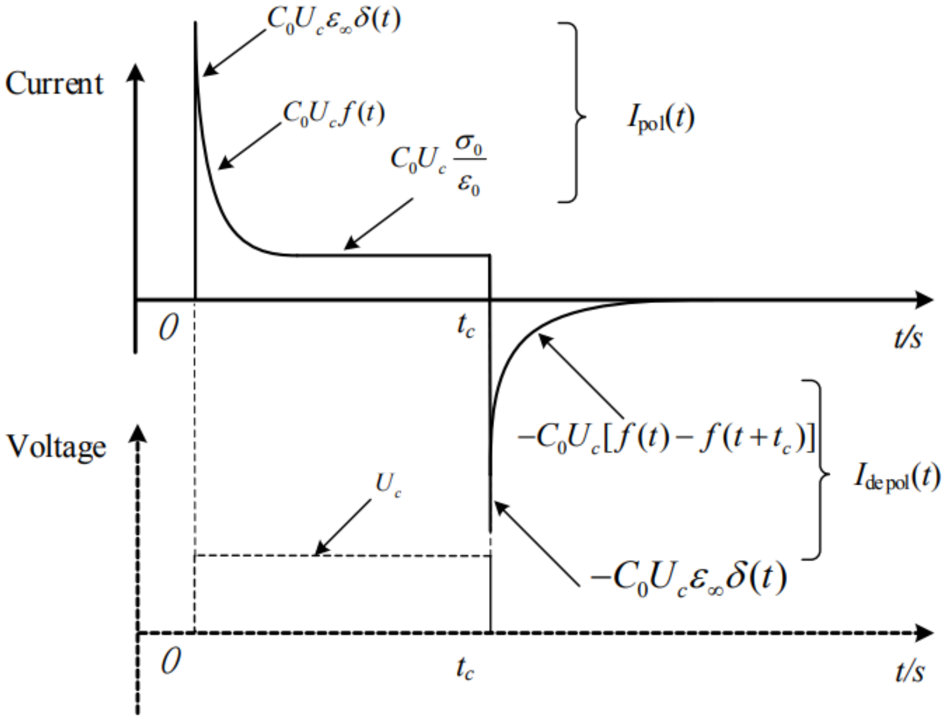


Figure 4: Typical waveform for polarization and depolarization currents [8].

The delta function (which is related to the momentary polarization) cannot be measured in practice and as the response function is monotonously decaying function together with a relatively large t_c the current terms can be simplified to the following:

$$I_{pol}(t) = C_0 U_c \left[\frac{\sigma_0}{\epsilon_0} + f(t)\right] \tag{5}$$

$$I_{depol}(t) = -C_0 U_c f(t) \tag{6}$$

From the measured currents it is possible to find the DC current which flows in the insulation. As seen from Figure 4 at time t_c the polarization current has stabilized. If the voltage is not switched of to measure depolarization, the stabilized current will be the DC current which flows due to the conductivity of the insulation [2], [7]. The DC current can then be found by:

$$I_{DC} = I_{pol}(t) - I_{depol}(t) \tag{7}$$

The DC current is considered constant with small variations depending on the measurement accuracy and as long as time t is not chosen too small. As the first few values have higher uncertainty due to the delta function from momentary polarization.

With the DC current known and using Figure 2, the conductivity of the dielectric can be calculated:

$$R_0 = \frac{V_0}{I_{DC}} = \frac{1}{\sigma} \cdot \frac{d}{A} = \frac{\epsilon_0 \epsilon_r}{\sigma C} \Longrightarrow \sigma = \frac{\epsilon_0 \epsilon_r \cdot I_{DC}}{V_0 \cdot C} \tag{8}$$

Since a perfect insulator does not exist, there will always be some form of conductivity. Therefore the DC current or conductivity may indicate the condition of insulators. Where σ is the DC conductivity of the insulator, I_{DC} is the DC current flowing in the insulator during the test. V_0 is the applied voltage and C is the measured capacitance of the test object. A is the area of a parallel plate capacitor and d is the distance between the plates.

The relative permittivity needed above can be calculated from the equation for capacitance in a dielectric functioning as a parallel plate capacitor:

$$C = \epsilon_r \epsilon_0 \cdot \frac{A}{d} \tag{9}$$

1.4 Frequency domain dielectric response

When conducting the dielectric response analysis in the frequency domain, the test object is subjected to an AC voltage as shown in Figure 5. With this method one measures the resulting voltage with the voltage divider and the current flowing through the insulation with an electrometer. The goal is to use the relation between the capacitive and resistive current to calculate the dielectric loss factor $\tan\delta$. This factor is the most common parameter to describe the dielectric loss of an insulation material. This loss is of course desired to be as small as possible. High dielectric loss may be a sign of insulation degradation and is given by the resistive part of the AC current, as shown in Figure 6 [3], [4], [7].

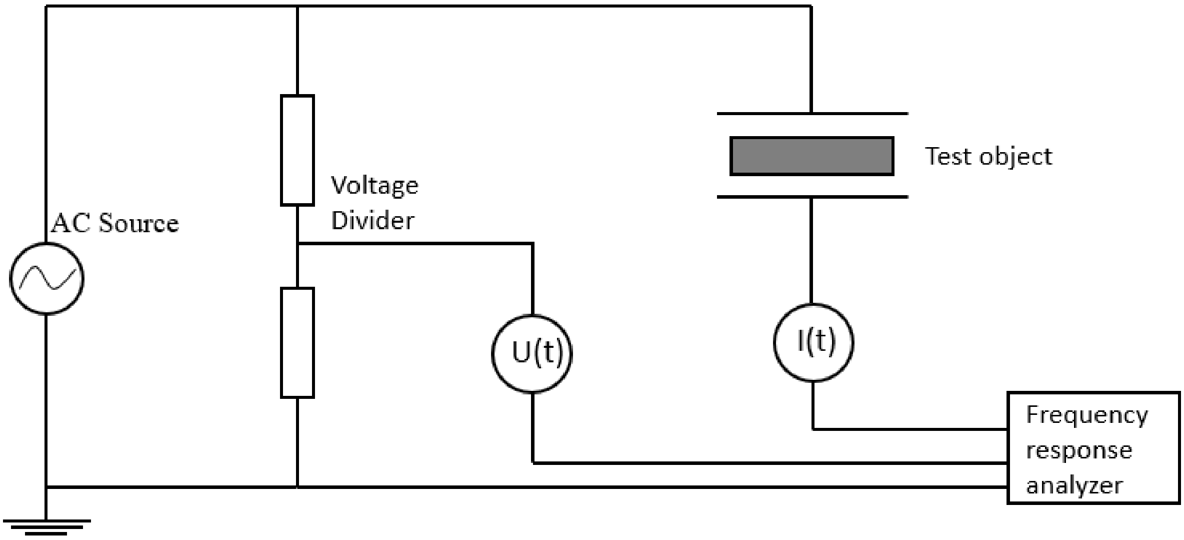


Figure 5: Schematic for measurement setup in frequency domain [7].

The current that flows through the insulation can be given by [7]:

$$\hat{I} = I(\omega) = jI_c + I_R \tag{10}$$

$$I(\omega) = \omega C_0 U_0(\omega)\left[j(\epsilon_r + \Delta\epsilon_r(\omega) + (\frac{\sigma}{\omega\epsilon_0} + \chi''(\omega))\right] \tag{11}$$

Where

- U_0 = applied voltage
- f = applied frequency
- C_0 = capacitance of the object
- ϵ_r = relative permittivity
- $\Delta\epsilon_r$ = change in capacitance
- $\chi''(\omega)$ = dielectric susceptibility which corresponds to the response function.

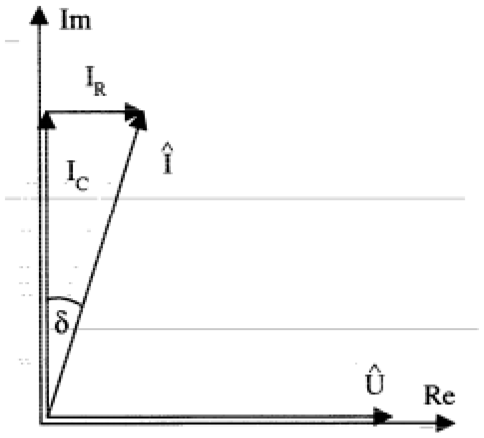


Figure 6: Phasor diagram of the voltage and current in the insulation [7]

From the phasor diagram one can see that the loss factor is dependent on the angle between the resistive and the capacitive components of the insulation current. In other words it is dependent on the complex permittivity, since the flux density $D(t)$ is lagging an angle δ behind the applied electric field, due to relaxation mechanisms. It is this phase shift which causes losses [4], [7], [10].

Due to the alternating voltage, dipoles will be constantly change directions. The dipoles can follow this change at lower frequencies, but not higher. This leads to a reduction in polarization, and therefore a reduction in relative permittivity, with increasing frequency. The loss factor can then be derived as done in [4]:

The applied electric field is given by:

$$E(t) = \sqrt{2}E \cdot \cos(\omega t) = Re\left\{\sqrt{2}Ee^{j\omega t}\right\} \tag{12}$$

Where only the real E - vector is chosen. As mention the flux density will lag an angle δ behind the field.

$$D(t) = \sqrt{2}D \cdot \cos(\omega t - \delta) = Re\left\{\sqrt{2}\vec{D}e^{j\omega t}\right\} \tag{13}$$

The D - vector is then written as:

$$\vec{D} = De^{-j\delta} = \epsilon_0\vec{E} + \vec{P} = \vec{\epsilon_r^*}\epsilon_0\vec{E} \tag{14}$$

Where $\vec{\epsilon_r^*}$ is the complex relative permittivity which is expressed as:

$$\vec{\epsilon_r^*} = \frac{\vec{D}}{\epsilon_0 \vec{E}} = \frac{D}{\epsilon_0 E} \cdot e^{-j\delta} = \frac{D\cos(\delta)}{\epsilon_0 E} - j\frac{D\sin(\delta)}{\epsilon_0 E} = \epsilon_r' - j\epsilon_r'' \tag{15}$$

From this, the definition of the dielectric loss factor is given by:

$$\frac{\epsilon_r''}{\epsilon_r'} = \frac{\sin(\delta)}{\cos(\delta)} = \tan(\delta) \tag{16}$$

The dielectric loss factor is one of the variables of interests in the thesis. It is impossible to distinguish between dielectric losses and losses caused by conductivity [4]. The losses can therefore be given by:

$$p = \omega\epsilon_r'\epsilon_0 \tan(\delta) \cdot E^2 \tag{17}$$

Where the dielectric loss factor can be written in two parts.

$$\tan(\delta) = \tan(\delta_1) + \frac{\sigma}{\omega\epsilon_r'\epsilon_0} \tag{18}$$

In the first part, the subscript 1 refers to the contribution from just the polarization. While the second part is the contribution from the conductivity of the insulator.

1.5 Relation between frequency and time domain

Instead of doing the measurements in frequency domain, the dielectric loss factor can be calculated with the use of Hamon approximation. The current transient in the dielectric has a decay function, or time dependence, given by:

$$I(t) = A \cdot t^{-n} \tag{19}$$

Sources have some different views in regards to the time dependence equation. In [7] and [11], $0.3 < n < 1.2$. While [12] states $0.5 < n < 1$.

In either case, the Hamon approximation is written as:

$$\tan(\delta)(f) \approx \frac{I_{pol}(f)}{\omega C_0 U} = \frac{I(measured\ at\ t = \frac{0.1}{f})}{2\pi f C_0 U} = \frac{I \cdot t}{0.63 \cdot C_0 U} \tag{20}$$

Where

- U = applied DC voltage [V]
- C_0 = capacitance of measurement object [F]

- I = polarization or depolarization current [A] measured at given time t [s]
- f = frequency, equal to $\frac{0.1}{t}$

As stated in [11], this equation is considered more than satisfactory to approximate the dielectric loss factor. Furthermore, both polarization and depolarization currents can be used for the approximation. However, polarization has been found to be more accurate in translating time to frequency domain. The use of depolarization current for Hamon approximation can still be useful tool for analysis [13] but there can be significant differences in the calculated dielectric loss factor depending on which current used.

2 Test Method

2.1 Test objects

Based on the conclusions of the specialization project [10], a Megger, or Megohmmeter, will be used for dielectric response analysis in the time domain. In the specialization project, some simple generator bars, made by NTNU for lab courses were used for the initial testing. For the master thesis, actual industry used generator bars from a Norwegian hydropower plant will be available. The very same bars have been used for research in the field of partial discharge (PD), [14], [15] and comes from a generator decommissioned in 2017. The three phase 95 MVA/13kV generator was installed in 1965 and has been in operation for 52 years at the time of decommission. The removal of the generator was due to a planned upgrade and it was considered to be in a healthy state. Condition monitoring showed no excessive aging other than what was expected after a long service. The stator temperature was below $90^\circ\ C$ at high loads, significantly lower than groundwall insulation temperature class F of $155^\circ\ C$. The bars consist of Roebel transposed conductors with epoxy impregnated mica tape. The semiconductive layer has been repaired with the use of conductive paint CoronaShield P8003. The measurement area, or measurement electrode, of each bar is considered to be 1.5 m long. There are some small variation in length for each bar which can be ignored. The capacitance of the bars were measured at $100Hz$ to be 2.840 nF. The internal insulation damages of each bar is unknown, so some variation in the test data can be expected for the otherwise closely identical bars shown in Figure 7.

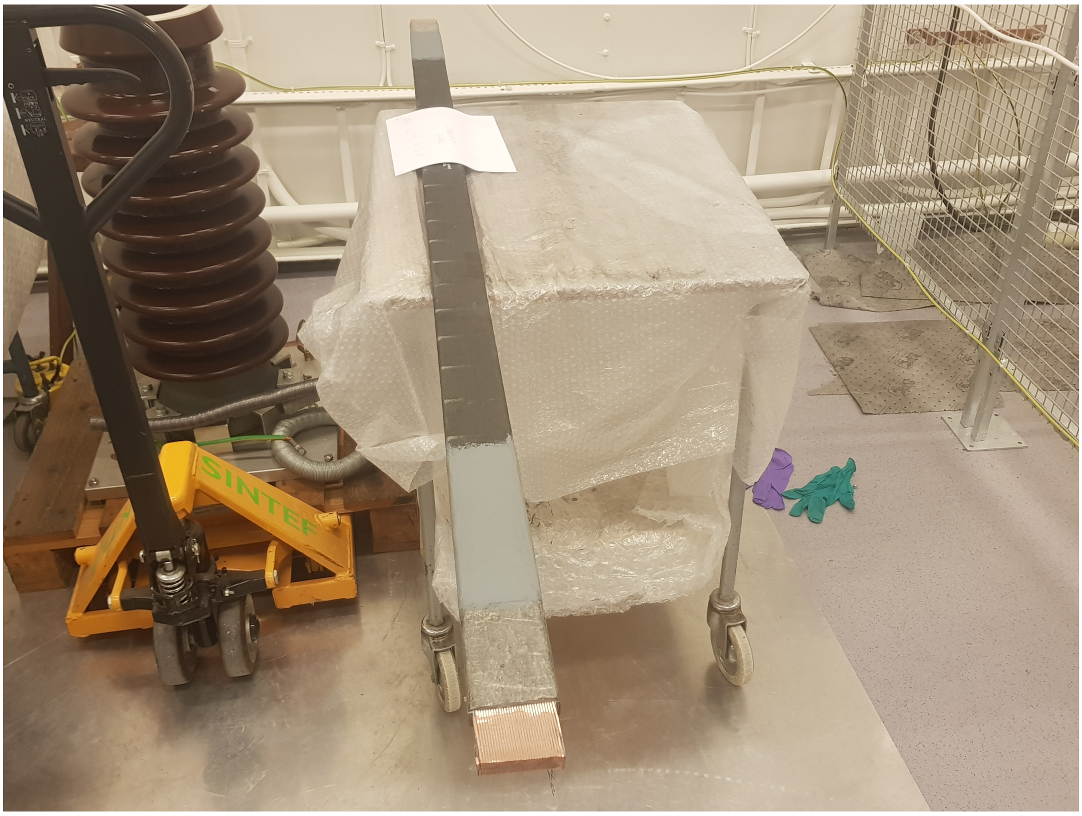


Figure 7: One of the generator bars which will be tested on. The black area is the approximately 1.5 m long measurement area where insulation current will be measured from. The light gray area is the Coronashield painting.

The geometry of the stator bars are shown in Figure 8. Using these dimension together with equation (9), one can calculate the relative permittivity of the stator bars insulation.

The average area is considered a good estimation, using the circumference of the insulation layer and the conductor:

$$\begin{aligned}
A_{avg} &= \frac{O_{insulation} + O_{conductor}}{2} \cdot l \\
A_{avg} &= \frac{(7 \cdot 2 + 2.1 \cdot 2)\ cm + (6.3 \cdot 2 + 1.4 \cdot 2)\ cm}{2} \cdot 150\ cm \\
A_{avg} &= 0.252\ m^2
\end{aligned} \tag{21}$$

With the capacitor distance $d = 0.0035\ m$ and capacitance measured to be $2.840\ nF$, the relative permittivity is calculated to be:

$$\epsilon_r = \frac{C \cdot d}{\epsilon_0 \cdot A} = 4.455 \tag{22}$$

For epoxy mica insulation, the relative permittivity found in tables are usually considered to be 4 [4]. The calculated value is therefore considered close enough for this project. The deviation from 4 will not impact any further calculations other than a small change in magnitude, which are acceptable as there are no information on the bars actual relative permittivity.

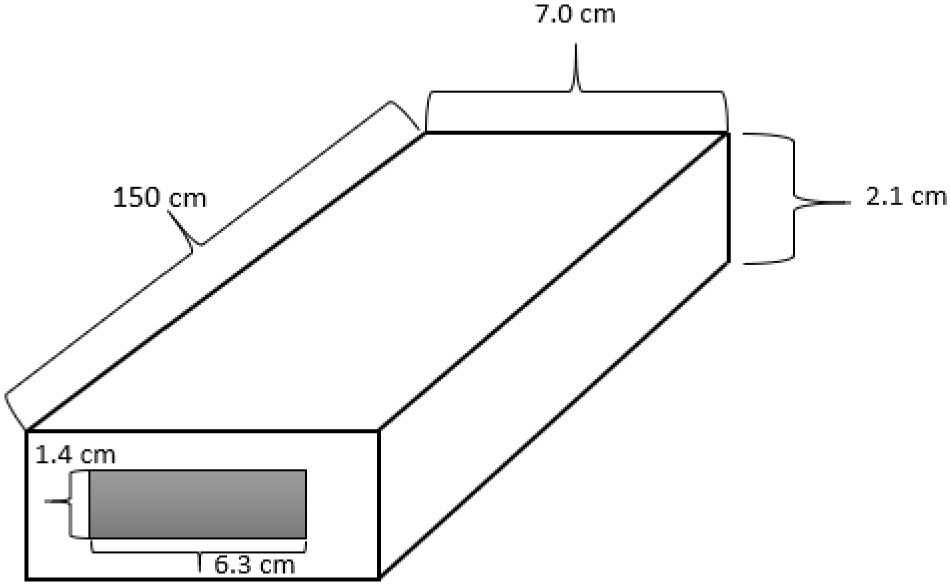


Figure 8: Geometry of the stator bar used for calculation of the relative permittivity.

2.2 Methodology

Testing will be conducted on 4 generator bars for 4 different temperatures, 20, 60, 90, 130 °C. The testing will also be conducted on 3 different voltage levels of 2, 5, and 10 kV. Once tests has been conducted for all bars, the testing will be repeated on the same bars after they have been subjected to thermal cycling. The time setup is changed from 15/15 in the specialization project to 30/30 in this thesis. Meaning 30 minutes of polarization and then 30 minutes of depolarization. According to Megger [6], most test object is usually fully charged after 10 - 30 min polarization time. Initial testing showed that there was still a relatively rapid decline of current after 15, meaning the test object was not fully charged and therefore time was set to 30 minutes.

According to literature [2], [6], the depolarization should be 10 times the polarization time to fully discharge the test object. This is not achieved with a 30/30 setup, however it was believed that given the significant increase in voltage after each test, the impact from the previous test would be considered insignificant. Testing this was done by running 2-5-10kV test in rapid succession with no grounding or break time in between. Then a test was conducted at 10kV after 24 hours of grounding the object, followed by another 10 kV test instantly after the 24 hour test. The results, presented in Figure 9 and Table 1, show some difference between long wait time and continuous testing with increased voltage. It is possible to see that the current will be a bit lower, about 10%, when the object is not fully discharged. As is expected since the charge current will be reduced due to some residual charge still existing at the start of the next test. For the purpose of this thesis, these variations are considered acceptable and rapid tests were also done by [16].

Most tests, independent of time setup, show some form of variation which can be due to the meggers own sensitivity as well as the position of measuring cables. These cables will be able to impact each other due to their capacitive elements and can cause difference in measurements based on how they are placed. Its impossible to maintain a constant positioning for the cables, as the test area will be used for another research project for half the day. The cables will be placed as similar as possible, and the positive port cable (red) will hung by ropes so it does not touch metallic material on the floor and is as far away from guard and negative port, which helps reduce the impact from cable positions. Furthermore, due to the delta function, the first values saved by the megger is considered to be uninteresting as they cant be correctly measured or used for further calculations. The megger is also incapable of being consistent for saving the first few values. Meaning both polarization and depolarization measurement may start anywhere from 0 seconds to 10 seconds into the test. The first values must then be removed in order to create plots and to analyze data. This is acceptable as these first saved data points can't be trusted.

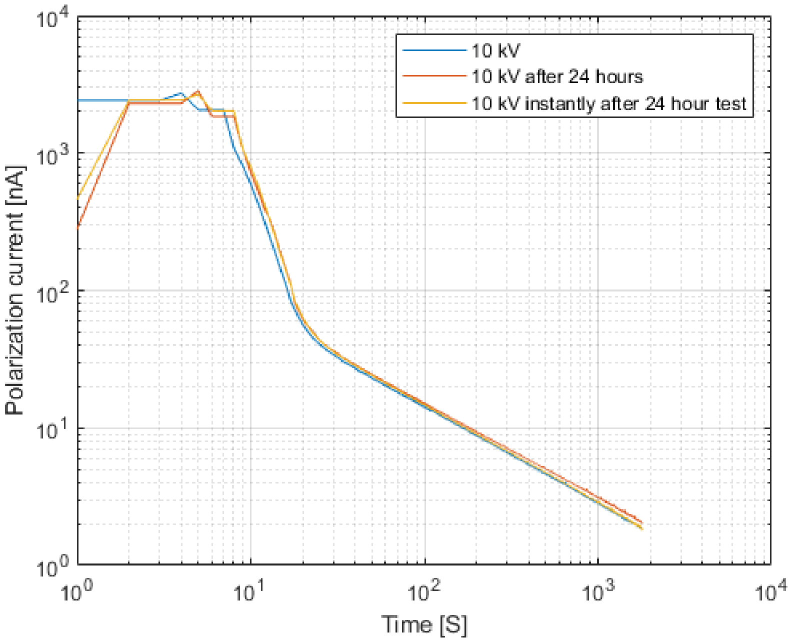
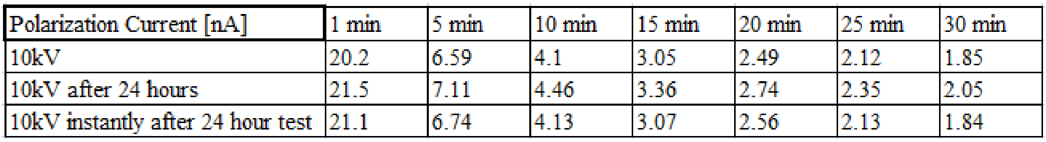


Figure 9: Polarization current as a function of time for a single bar. The impact of increasing the voltage and starting a new test without fully discharging a bar is small and considered acceptable.



Polarization Current [nA]	1 min	5 min	10 min	15 min	20 min	25 min	30 min
10kV	20.2	6.59	4.1	3.05	2.49	2.12	1.85
10kV after 24 hours	21.5	7.11	4.46	3.36	2.74	2.35	2.05
10kV instantly after 24 hour test	21.1	6.74	4.13	3.07	2.56	2.13	1.84

Table 1: Key numbers (polarization current) from testing the impact of increasing the voltage without allowing full discharge of the bar between tests.

Initial testing on the new bars also showed that surface leakage currents made about 50 % the total current measured. These findings were consistent for different voltages as opposed to the bars in the specialization project. Therefore the megger guard terminal will be used for the testing, meaning that measurements are performed only on the main insulation of the generator bars.

Thermal cycling

After all the bars have been tested, they will be tested again after being through thermal cycling. The cycling is performed as per the recommended practice from IEEE [17]. The bars are heated by being subjected to a current of 3.5 kA. This will heat the conductor from

$40° - 130° \, C$. They are then cooled with fans until the temperature reaches $40° \, C$ again. The thermal cycling is a form of rapid ageing simulation. It will allow for a comparison before and after cycling to investigate if this causes significant deterioration in the bars.

Setup

The test setup, as shown in Figure 10 - Figure 14, are also used in another project for analysis of partial discharges. Some extra components and objects will therefor be in the cell. Neither these components nor the actual testing of PD on the same object will significantly impact the test results. The connections follows the schematic shown in Figure 3.

Figure 10: Overview of the test cell. The large silver box on the left side holds the generator bars and will maintain temperature at the desired level. A significant amount of the equipment is used in the other project.

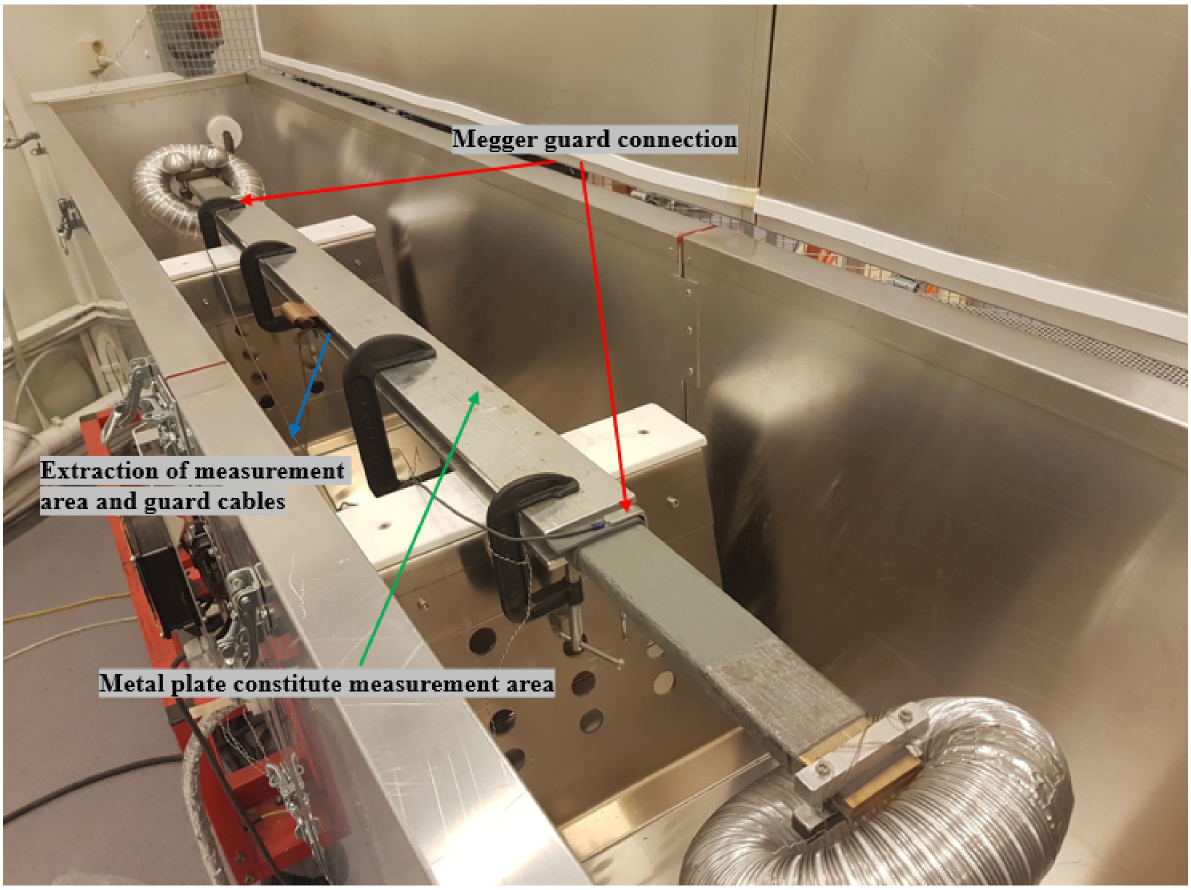


Figure 11: The generator bar inside the heat box. The guard connection is just beside the metal plate covering the middle of the bar. The metal plate is the measurement area which is connected to ground, which the megger negative port is connected to. Both the measurement area and guard are extracted through a small hole in the side of the box with heat resistant cables.

Figure 12: Connection to the conductor of the bar. Some corona protection is added for the other project.

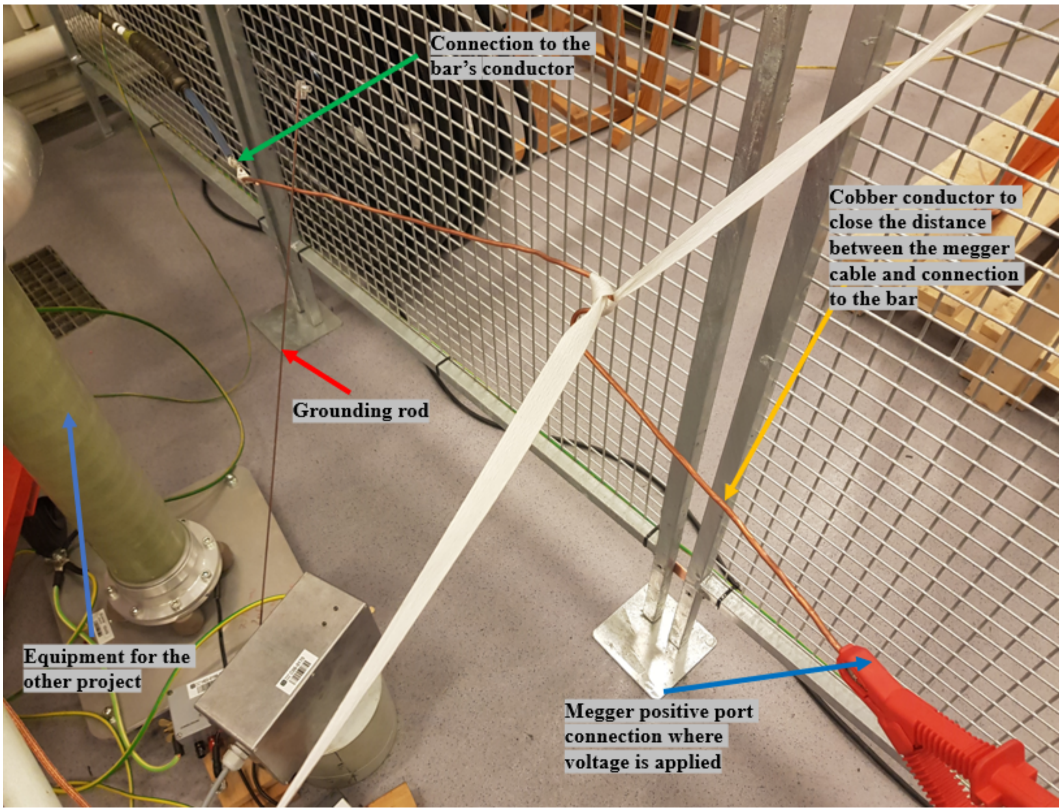


Figure 13: The connection from the Megger positive port (red) to the conductor via a copper rod. This is where voltage is applied to the stator bar.

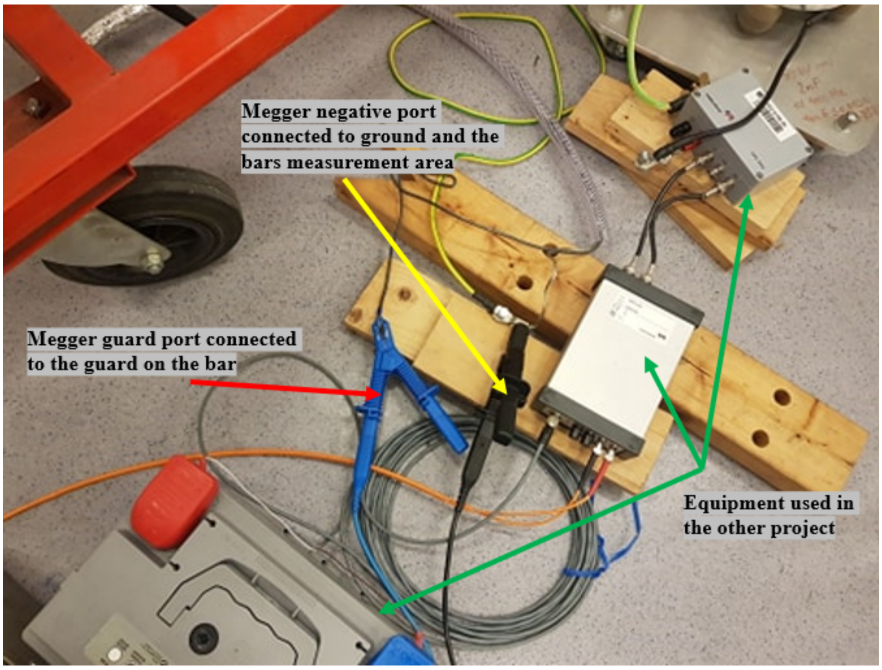


Figure 14: The Guard terminal (blue) is connected to the cable which in turn is connected to the guard clamps on the stator bar. The negative port (black) is connected to the ground cable which is connected as the measurement area. The other equipment seen here are used in the other project.

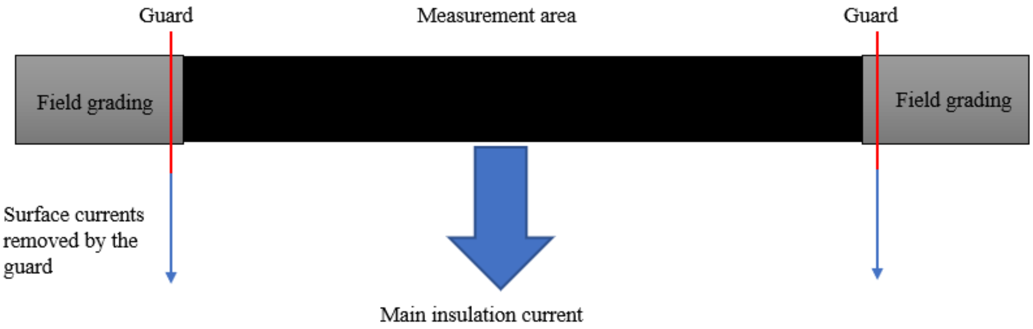


Figure 15: The current flow in the bar when conducting the tests. The guard will remove leakage and surface currents. Only the main insulation will then be measured on from the black measurement area.

Data handling

From the Meggers dielectric discharge test (polarization and depolarization tests) the data is saved in a table format. The megger only saves the measured current, time and a calculated insulation resistance. This table is copied to text files which then can be used either in excel, Matlab or similar programs. For this thesis a Matlab script has been developed in order to handle the data (see Appendix A). From Matlab, plots are made to analyze and interpret the data. The Meggers DC generator applies a voltage and measures the current flowing through the insulation, the resistance is calculated with ohms law. The current values will be used in the script to perform calculations and develop different plots of interests.

3 Test Results and discussion

In the following section, the results from the testing part of the thesis will be presented and discussed. As there are a significant amount of different test results, only key plots will be presented in order to facilitate the discussion. Most tests have been found to indicate either trends or similarities between the test objects and the impact of temperature and voltage. It is therefore not necessary to present all the developed plots as there are far to many.

3.1 Polarization and Depolarization currents

Polarization and Depolarization currents are presented in Figure 16 - 25. It is observed that the curves show similarities to the curves presented in the theory in subsection 1.3. Note that the depolarization curves are presented in absolute values (automatically done by the Megger) in order for the plots to be in log/log format. In all the curves, the first values plotted, are caused by the delta function part of the currents as the step voltage is applied. This is plotted as the Megger attempts to estimate the current at the start. The delta part is highly unstable, sometime the Megger will measure them as negative values and other times not. It also seems the Megger starts the plotting at random start times. Commonly the variations are from t = 0 to t = 5 seconds. These start values are not of interest for further analysis and are only shown to provide context. After about 1 minute the values are usually considered actually measured and therefore usable values [6], [8].

The first important observation to be made is the significant variation or noise in measured currents for tests on lower temperatures and voltages as seen in Figure 16 and 17. This is common for all measurements at 20 °C 2 kV and in some cases also occurs at 20 °C 5 kV and 60°C 2 kV. The noise is found to commonly be a current variation of about 20-30 ± % per second. When the megger starts to measure the currents at 1 nA and below, the significant variations starts. Indicating that the meggers sensitivity is around this area. The more significant variations starts to occur for all bars when the measured current reaches 0.68 nA. At this current the megger measures the maximum resistance of 3 TΩ. Up until this point, the resistance changes as the measured current does. After reaching this max resistance, the currents variation grows greater and the resistance will be shown as 3 TΩ for the remaining duration of the test, while still decreasing the current. This indicates that the Megger can't accurately measure the current after reaching this point and therefore begins to extrapolate the current values until the test is over.

This reduces the credibility of the measurements at low voltages and temperatures when the current reaches 1 nA. Tests are considered to have low credibility if there is significant noise, the polarization current is measured lower than depolarization or severe test anomalies are observed. Low credibility is discussed at length in subsection 3.2. The megger only reaches the maximum resistance on the 20 °C 2 kV tests. For all other tests, noise seems to be dependent on the low current around 1 nA. Above 20 nA, little to no noise is observed. The 20 °C 2 kV tests also showed some problems with the testing itself. Several times the maximum resistance was reached in under 1 minute, leading to the test stopping at that point and had to be restarted. In some cases the tests would work on the first try, in others the test would needed to be restarted up to 10 times before a full 30/30 test could be conducted.

There was also the problematic case of bar O162B at 20 °C 2kV shown in Figure 18. For this test, the maximum resistance was reached after 20 seconds, in which it should have ended prematurely like for the other cases experiencing this. However, the Megger instead started measuring negative numbers, before skipping 23 minutes of measurement time and then continuing with negative numbers. This bar had then normal discharge plotting but the polarization current results were unusable. The test could not be repeated due to time constraints. It does give more evidence that there are clear issues with the Megger on these object at low temperatures and voltages. Particularly as these tests all produce values in absolute value, meaning negative numbers should not be measured at all. The fact that depolarization current seemed to be measured as expected, means that the meggers problems are mostly caused by the resistance in the polarization current measurements. There are no resistance for the depolarization and these currents also show far less severity of the noise when reaching 1 nA.

The amount of noise experienced are dependent on how early the maximum resistance is reached. For bar O120B and O163B, the maximum resistance were reached after 6:47 and 5:21 minutes respectively. While O117B, which shows the least amount of noise, reached maximum resistance after 16:26 minutes. All three reached it at the same current of 0.68 nA. The comparison of all bars at 20 °C 2 kV are shown in Figure 16. As the Megger most likely does some form of extrapolation for the remaining time, it is reasonable to believe that the longer it takes to reach maximum resistance the more accurate the measurements. Which is seen as O117B shows the least amount of noise and does not have a lower polarization than depolarization current.

In Figure 19 and 20 it can be observed that the polarization current during some of the test course has a lower value than the depolarization current. This means that the DC current will become negative, which breaks with the theory and is considered impossible. This will be presented and explained more clearly in subsection 3.2. It does indicate the problem when the Megger reaches the maximum resistance, as it estimates the current incorrectly after that point. Leading to lesser current for polarization than depolarization. 20 also shows that negative DC can occur for tests that does not reach maximum resistance, but only has a low measured current of 1 nA and below during the test course.

Based on the results, it is assumed that the Megger applies the voltage as desired, meaning the charge as well as the discharge of the object is occurring correctly. The problem arises when the measured current is so low that it reaches the sensitivity level of the Megger. The sensitivity is related to the maximum resistance the Megger can measure, which leads to incorrect current measurements. The Megger is therefor considered unsuitable for dielectric response measurements on object which will lead to currents lower than 1 nA during the course of testing. Keep in mind that this sensitivity level of around 1 nA is only observed when measuring the polarization current. The depolarization current show no significant increase in noise when reaching these low currents, only natural variations are observed. This is what leads to the belief that the problem is only related to the resistance calculated by the Megger, as there is no such resistance for the depolarization measurement. This means that even for these low currents, as long as depolarization is used for analysis, the Megger might still be suitable for this condition assessment method. It is still recommended that higher voltage and temperatures be used in order to get both polarization and depolarization current measurements.

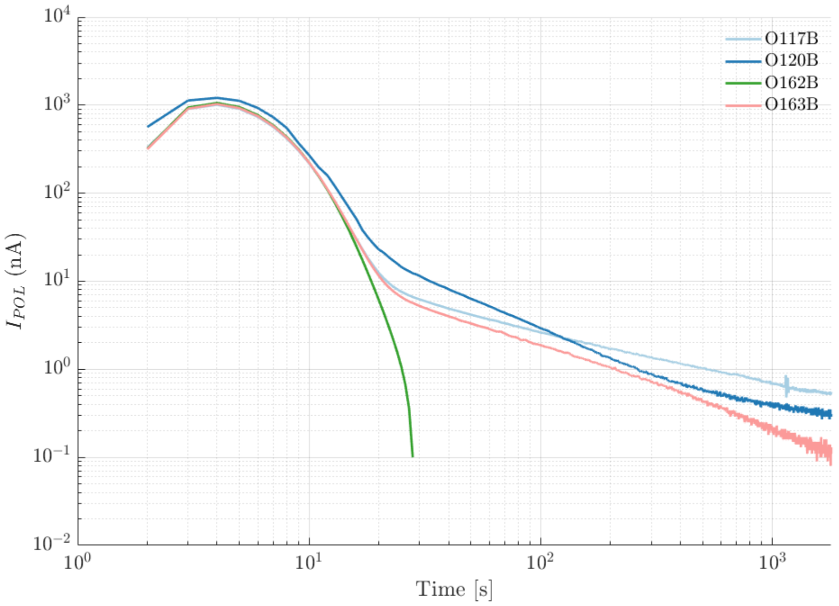


Figure 16: Polarization current for all 4 bars at 20 °C 2 kV. Showing the significant amount of noise caused by currents lower than 1 nA. O162B is seen to rapidly fall towards 0 before only measuring negative numbers.

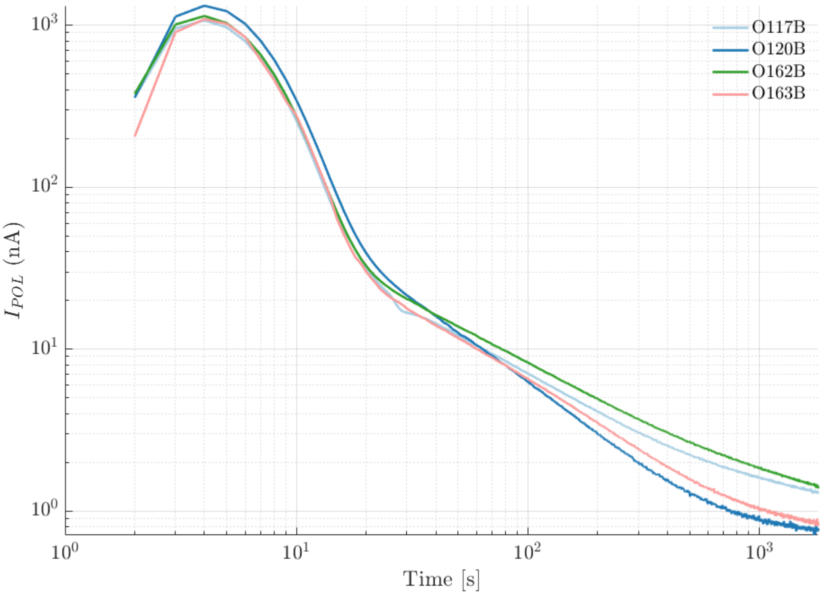


Figure 17: Polarization current for all 4 bars at 60 °C 2 kV. Although more severe on 20 °C tests, significant noise occurs as the long as the currents reaches 1 nA.

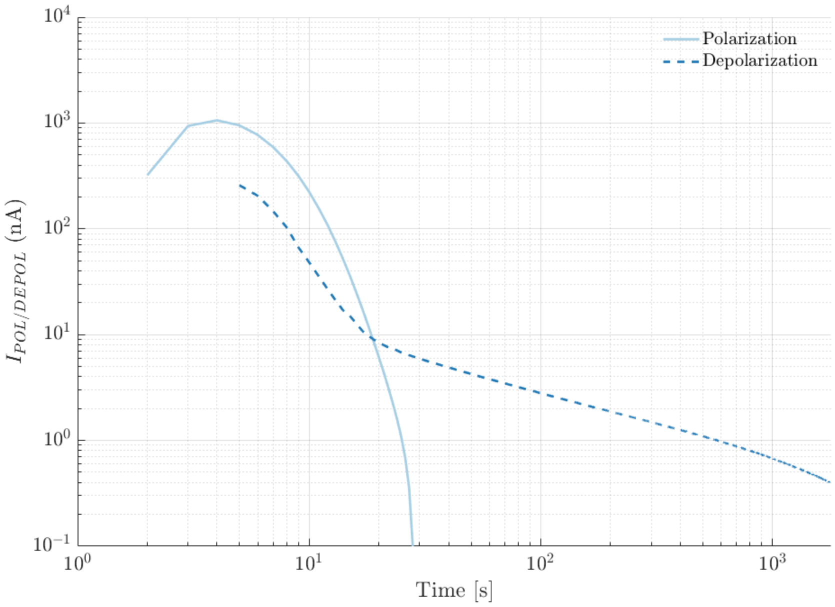


Figure 18: Polarization and depolarization currents for bar O162B at 20 °C 2 kV. The megger could not correctly measure the polarization current, while the depolarization currents could be measured as normal. Indicating that the meggers problems is most likely caused by the resistance only measured during the polarization time.

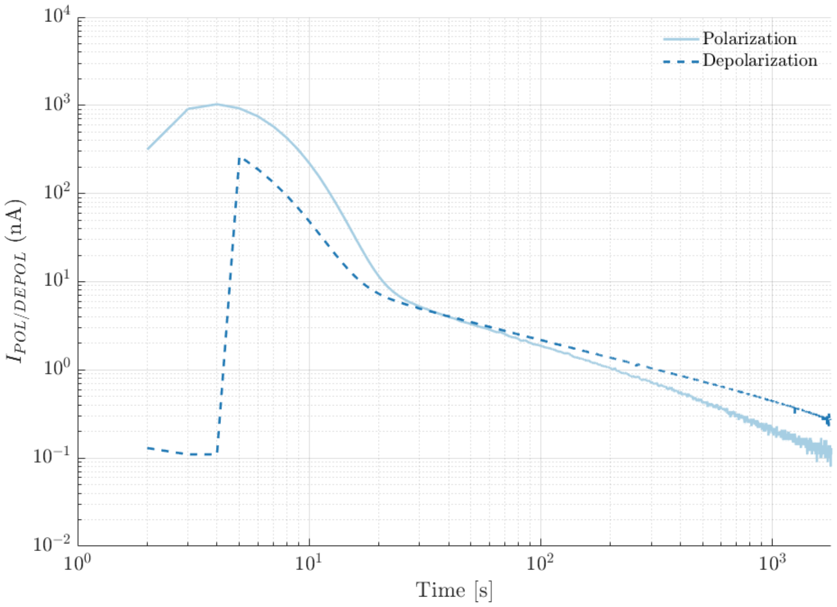


Figure 19: Polarization and depolarization currents for bar O163B at 20 °C 2kV. The plots shows a case where polarization currents at a certain point is measured lower than depolarization.

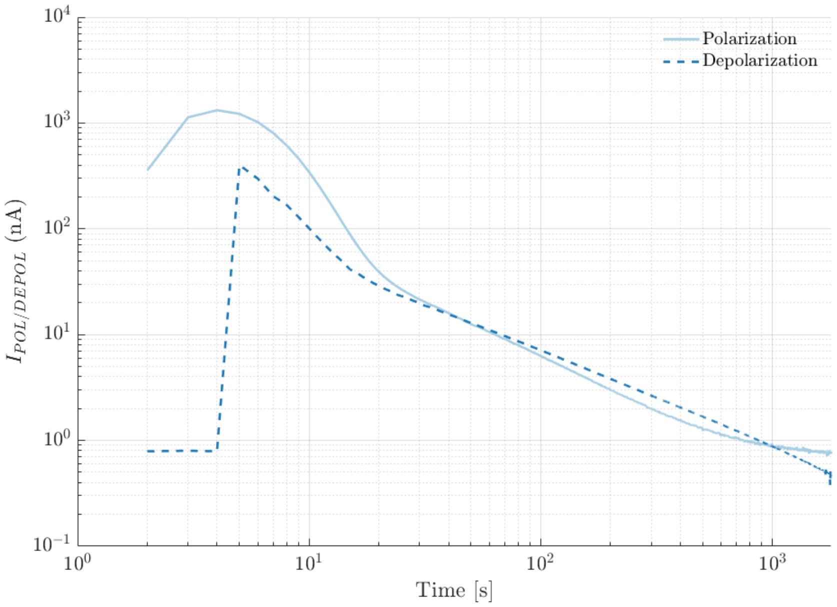


Figure 20: Polarization and depolarization currents for bar O120B at 60 °C 2kV. Showing that although most common for 20 °C test, the polarization current can be incorrectly measured as lower than depolarization current at 60 °C tests.

As shown in Figure 21 and 22 the higher the voltage and temperature the closer the measured curves are to theoretical curves. For all 90 and 130 °C tests, there are no significant noise due to the currents being higher than 1 nA and higher than 20 nA. The maximum resistance is not reached, so the megger is not incorrectly estimating values. The temperature is the greatest cause for this as increased temperature will reduce the insulators resistance. Increased voltage will of course increase the current as well, leading these tests to be more accurate and credible than the 20 and 60 °C tests. In Table 2, presented in subsection 3.2, it is shown which bars give credible test results for the different tests.

None of the curves manages to reach a flat stable DC current during the set time of 30 minutes polarization and 30 minutes depolarization. In particular it can be observed that the depolarization current is almost a straight line while the polarization current is flatting out more, though not completely. This is because the the set time for testing is not long enough to fully charge and especially fully discharge the the bars for each test. As explained in subsection 2.2, this will impact the following tests but within acceptable levels. The impact this has on further calculation of interesting data, e.g the DC current/conductivity and dielectric loss factor, is of much significance. In order to achieve the perfect plot with a clear stable DC current, the measurement time must be much longer than what is practical for a master thesis. It is important to take note of this for future work in the subject in case a more detail oriented analysis is to be undertaken. If the method is to be used in the field, long test time will not be feasible as well. Therefore the validation of the method with short test time is considered important for practical use of the method.

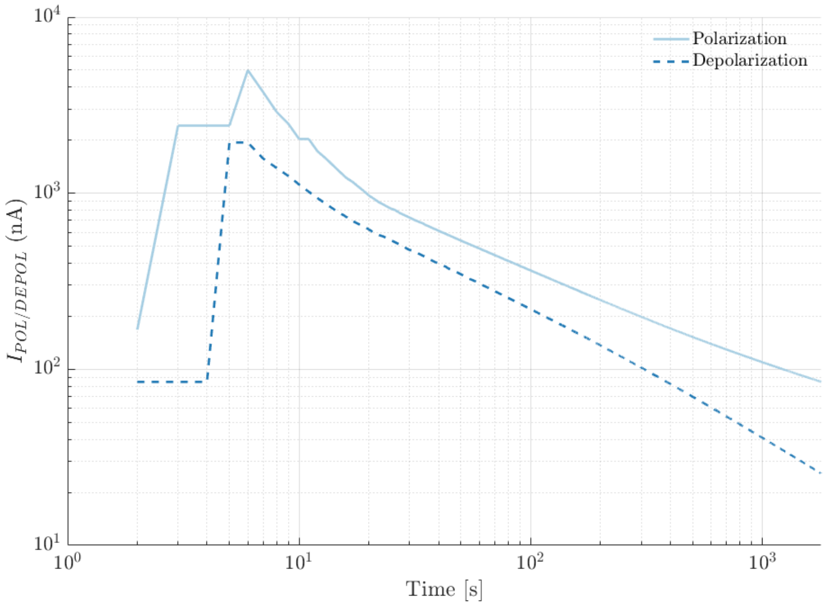


Figure 21: Polarization and depolarization currents for bar O117B at 90 °C 10kV. The currents does nor reach the 1 nA sensitivity level making them more similar to the literature. These plots are not able to reach flat DC current in the short test time.

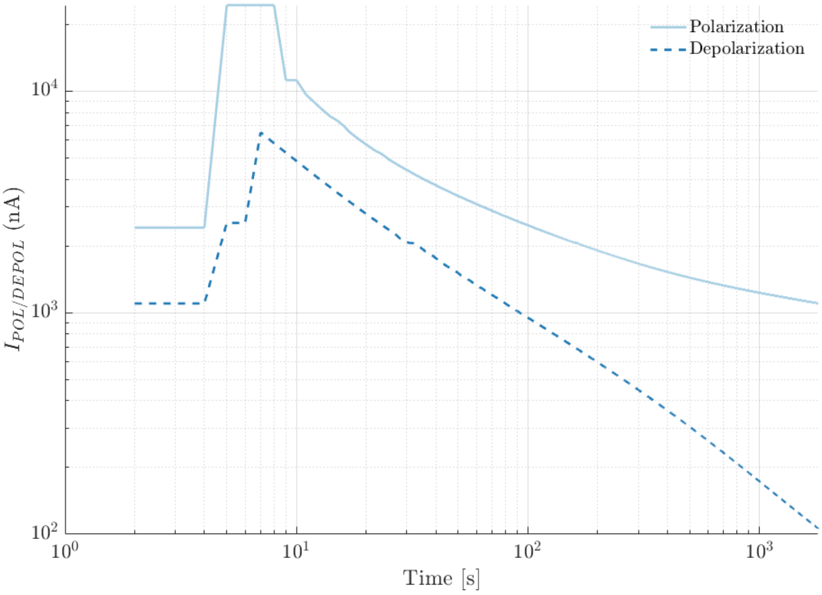


Figure 22: Polarization and depolarization currents for bar O117B at 130 °C 10kV. At the highest temperature and voltage the polarization currents flattens out more as opposed to the 90 °C test presented above. Showing that bars may vary rather significantly in behavior from test to test.

The bars are in theory supposed to be, or close to, identical with some variation expected. There are some differences observed, which causes are unfortunately impossible to determine for certain. When comparing the polarization currents for all bars, as shown in Figure 23 - 25 it is observed a rather significant difference between some bars, while other bars show more close test results. What is rather interesting is the fact that O120B stabilizes at the highest current for two tests, 20 °C 10 kV and 60 ° 10 kV. For the other tests, excluding those where the maximum resistance were reached, it has the lowest current. It is difficult to find the exact reason for this. It appears that the insulation resistance in O120B is decreasing less for the same temperature increase in other bars. This can be due to a difference in deterioration between the bars. It is also possible that it is just two test anomalies occurring on lower current tests as it happened in only two cases. It does appear that the bars have different reactions to the temperature, meaning most likely that the insulation of the bars vary in condition. For the 90 and 130 °C test, the observed trend is that O120B has the lowest current, followed by O163B and finally O162B and O117B with the highest currents. Where O163B and O117B are so similar in the plots its difficult to determine which has the highest and lowest current, as they often interchanges their position. This shows the importance of having a baseline value for the bars when they are unaged, in order to compare with results after years of service. Was this always the case caused by some difference in manufacturing process and what would the measured currents be when the bars were unaged? Without this prior knowledge it is difficult to say which condition the different bars are in and what causes different behavior to identical test setups.

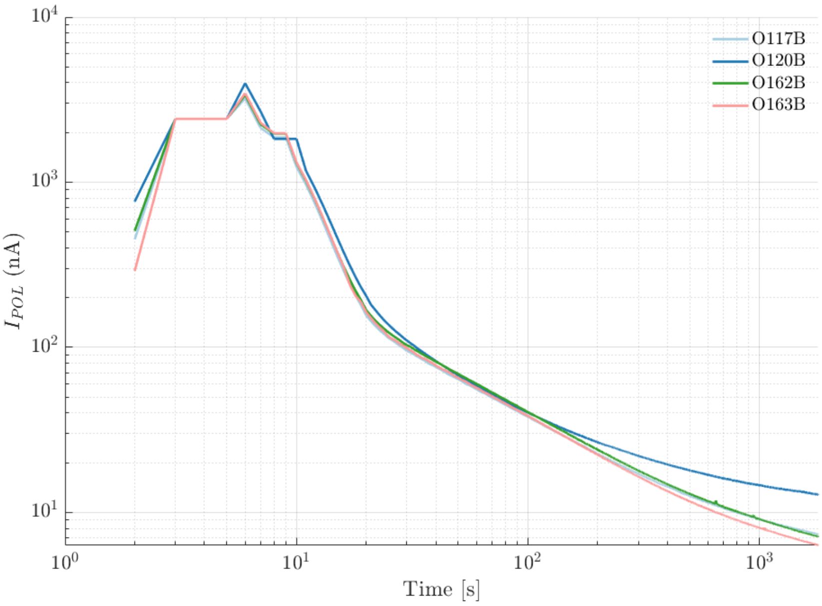


Figure 23: Polarization current for all 4 bars at 60 °C 10kV. It is observed that bar O120B stabilizes at a higher current than the other bars as opposed to the more common observation of having the lowest current.

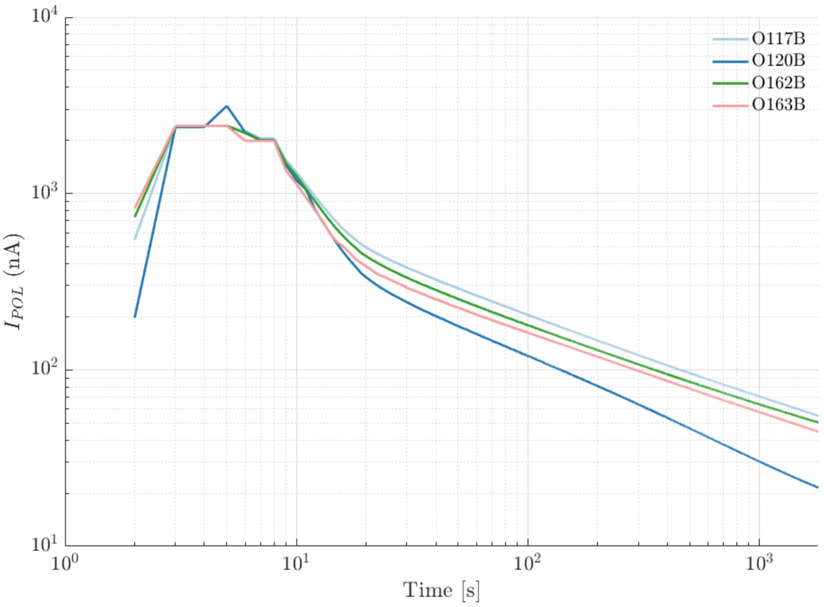


Figure 24: Polarization current for all 4 bars at 90 °C 5kV. Most bars have closer results on higher temperatures and voltages while O120B has significantly much lower currents.

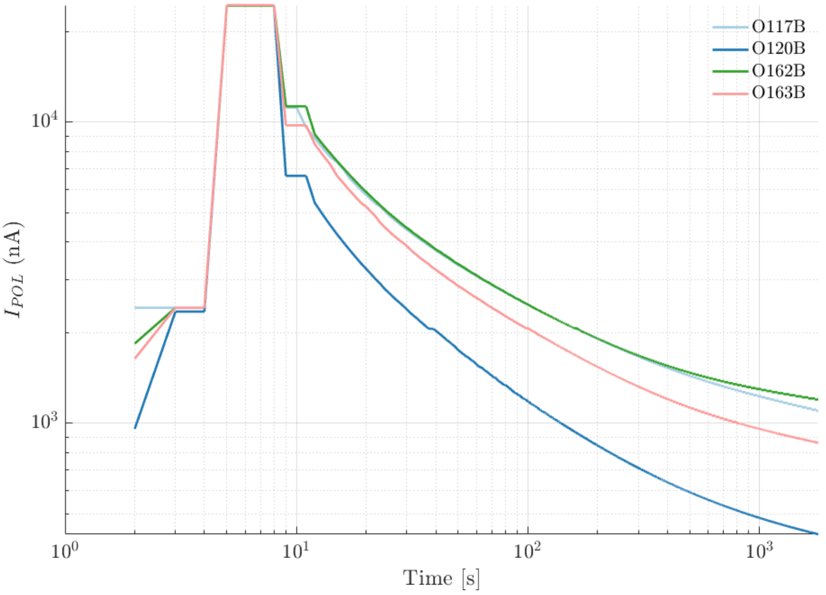


Figure 25: Polarization current for all 4 bars at 130 °C 10kV. At the highest temperature and voltage both O120B and O163B tends to deviate from from the other two bars. There is therefore most likely observed a difference in deterioration leading to the difference in measured currents on the bars.

3.2 Stabilized DC current

The DC current is a good indicator of deterioration as it fully depends on the insulators conductivity. The higher the DC current is, the more conductive the insulator, which is undesirable. The DC current is found as presented in subsection 1.3 and the plots are presented in Figure 26 - 31. DC plots are also a good way to investigate which tests are not performing satisfactory and has low credibility as discussed in the previous section. Just as with the polarization and depolarization curves, there will be a large peak in the beginning before the curve flattens. It is even more clear in these plots that there are problems with conducting dielectric response with a megger on lower temperatures and voltages for these objects. Several bars gets a negative DC current, which is due to the depolarization current being higher than the polarization current. Such results are considered impossible from a logical point of view and caused by the megger incorrectly estimating the polarization current. Either when maximum resistance is reached or a low enough current around the 1 nA sensitivity level is measured. This is particularly clear in Figure 26 and 27, where significant noise or variations are observed. In addition to this, some curves falls rapidly towards zero. This is because the DC current reaches negative numbers, which is removed in order to make log/log plots. Here it is also possible observe that O117B does not have a negative DC current as it took much longer for the test to reach maximum resistance.

Therefore allowing the megger better estimation of the current. The test results in which the DC current is negative at parts or all of the test course are considered to be non credible results. This also shows that a test does not need to reach 0.68 nA in which maximum resistance is reached for the test results to be considered incorrect. As long as the polarization currents reaches 1 nA and below it is possible that the DC current becomes negative, evident of the results in Figure 27. This evidence suggest that the megger is generally unsuited for dielectric response measurements on these objects if any measured current falls below 1 nA.

In Figure 28, O120B shows some part of the test course being removed as it was negative numbers. In this case this is still considered reliable test results as this occurs before 1 minute has passed, where the numbers cannot be truly trusted. The remainder of this test result coincides with the trends observed for both O120B and the other bars. This was most likely due to some brief measurement error in the megger which was quickly corrected.

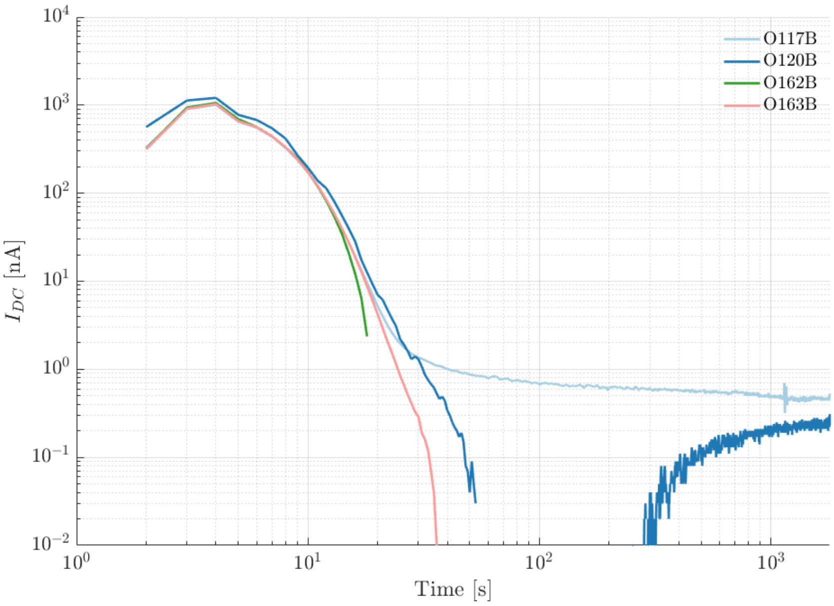


Figure 26: DC current for all bars at 20 °C 2 kV. With the exception of O117B, all bars had higher depolarization than polarization current leading to negative DC current.

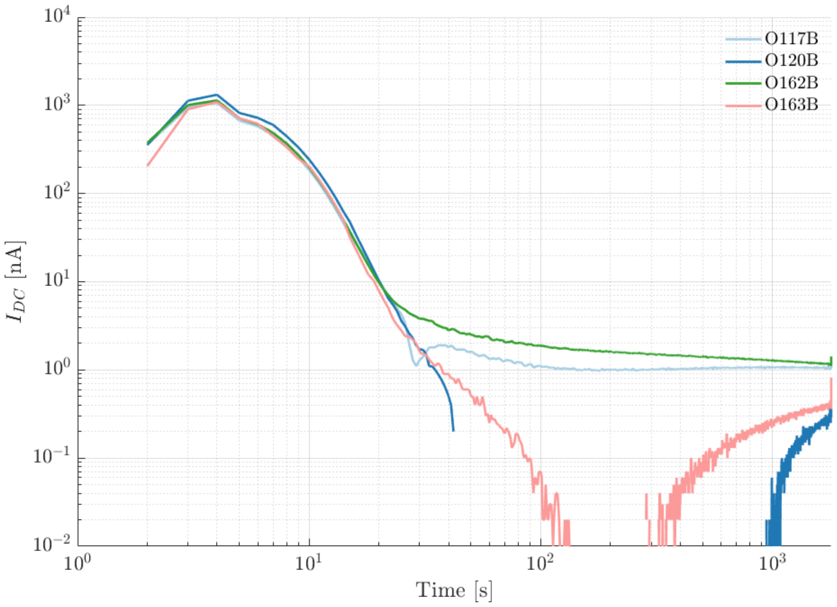


Figure 27: DC current for all bars at 60 ° C 2 kV. Tests that does not reach the maximum resistance can still be incorrect. As long as the polarization current reaches 1 nA and below the DC current may become negative, a clear sign of incorrect measurement by the megger.

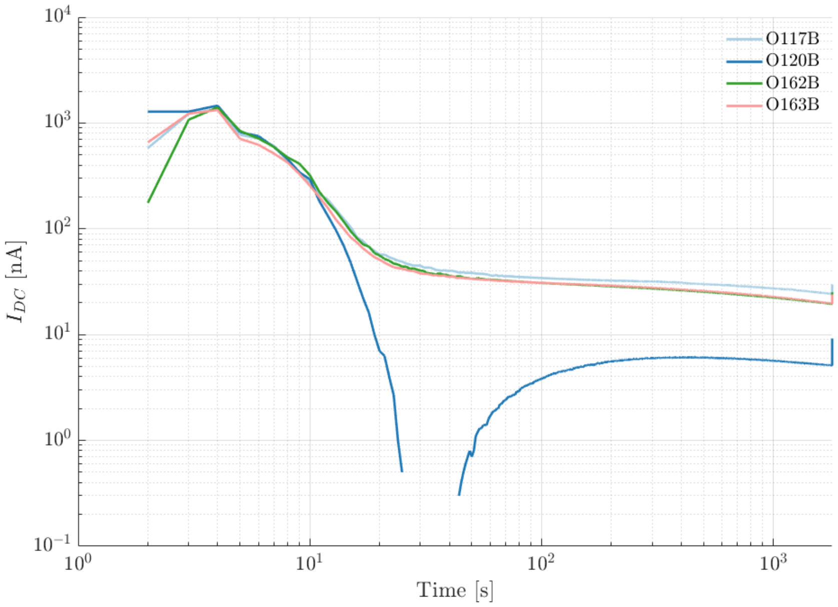


Figure 28: DC current for all bars at 90 °C 2 kV. The negative part of O120Bs test course is most likely a test anomaly. Since it occurs before one minute has passed and is quickly corrected it is still considered a credible result. The remainder of the test course is as expected and follows the trends of the bars performance.

Once more, the higher temperatures and voltages as seen in Figure 29 - 31 produces the most credible results. The plots show no significant variation given their relatively high polarization and depolarization currents. The same trends as seen in subsection 3.1 with O120B having the lowest current with the same two exceptions in 20 and 60 °C 10 kV tests. Just as with the polarization currents it is also observed that O120B and O163B show the most difference in measurement to the other bars, while O117B and O162B with the highest currents are found to have much closer results. The short test time is again observed to be preventing a flat stable DC current, but it is considered acceptable and usable for further calculations and analysis. Based solely on the DC plot trends it appears O120B performs best with the lowest DC current and therefore lowest conductivity in the insulation. Followed by O163B and finally O162B and O117B. The results of O117B and O162B are again in many cases so close its difficult to determine which has the higher or lower current. They also do interchange their position in several test cases.

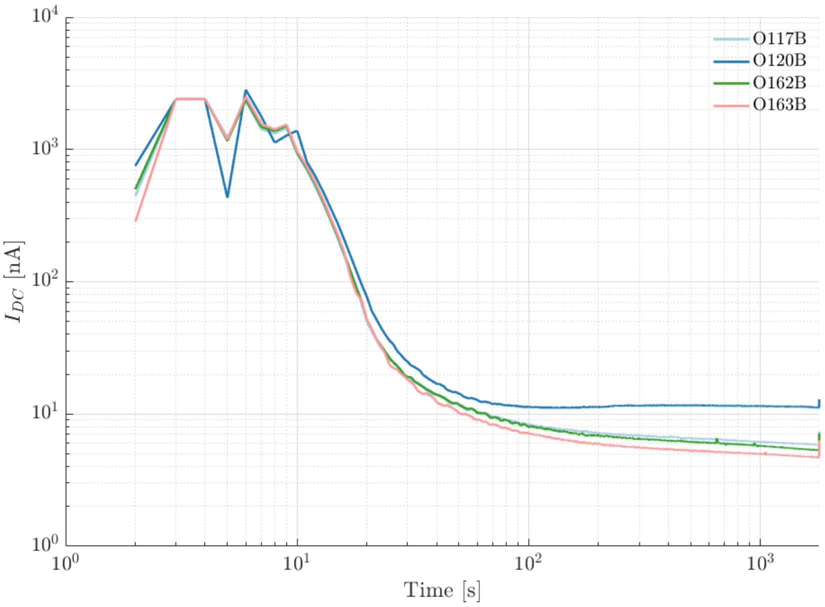


Figure 29: DC current for all bars at 60 °C 10 kV. Just as with polarization current, the plots shows one of the deviation with the trends of bars performance with O117B having the highest current on this test.

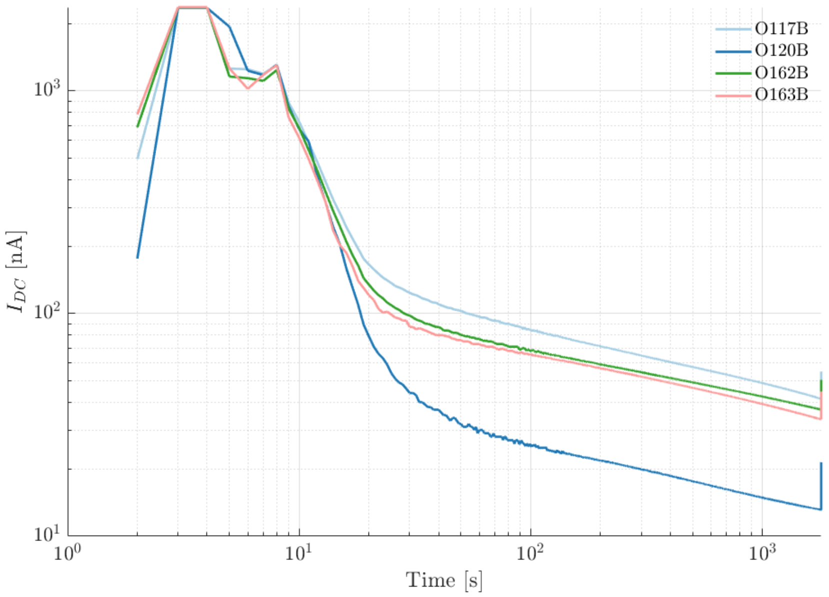


Figure 30: DC current for all bars at 90 °C 5 kV. The trend showing the bars performance with O120B having the lowest current, followed by O163B, O162B and finally O117B

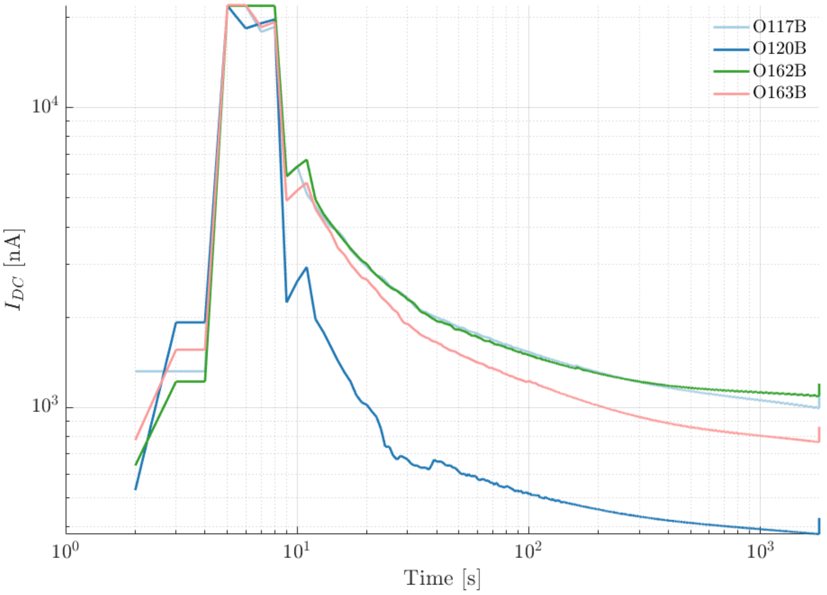


Figure 31: DC current for all bars at 130 °C 10 kV. The plots are not flatting completely to a steady DC current due to the short test time. The trends are visible here, with an example of the case where O117B and O162B are extremely similar in measurements and interchanges their position a bit at the end.

Based on the results from polarization and depolarization current measurements, as well as the DC currents, a table is produced for comparisons. Table 2 is a summary of which tests give credible numbers for the different bars. Significant variations or noise as well as whether or not a negative DC current was found is the basis for whether a result is considered credible or not.

	20° C	60° C	90° C	130° C
2 kV	None	O117B O162B****	All**	All**
5 kV	None***	All*	All	All
10 kV	All*	All	All	All

Table 2: Bars which gave credible results in the different tests are given in the cells. Red means none of the results were credible. Yellow for some of the results being credible or questionable, green for all results being credible and blue for results being credible but some strange behavior were observed.

* = Although credible, noise caused by low current observed.

** = Rapid decrease in polarization current for some of the tests before increasing towards flat DC level which leads to a dip in DC plots. Still considered credible as the dip occurs early in the test.

*** = All bars on 20 °C 5 kV have plots according to literature but some experience variations/noise to such extent that the results are questionable.

**** = O120B and O163B has negative DC plots due to incorrect polarization measurements.

It is clear from these initial results that the method has some issues when there is a low current. The most significant inaccuracies and occurrence of negative DC current occurs for tests lower than 1 nA. Currents lower than 20 nA have a tendency to noise, though they are not as severe. All tests which are above 1 nA during the test course are considered credible. While currents above 1 nA but below 20 nA are most likely credible, with some noise. If a megger is to be used a high voltage must be the basis for all testing in order to achieve credible information.

3.3 Dielectric loss

The dielectric loss factor tan δ, as explained in subsection 1.4, is one of the variables used with dielectric response to investigate an insulation's condition. An increase in deterioration may lead to increased dielectric losses. The loss factor will be investigated as a function of time, or low frequency, as well as a function of voltage and temperature.

3.3.1 Dielectric loss as a function of voltage and temperature

Ohms law dictates that when the resistance remains constant, a doubling of voltage should lead to double the current. Dielectric response is based on Ohms law and dielectric losses can be used to investigate linearity in the test objects. Any deviation from linearity may indicate deterioration or it may indicate the existence of mechanisms inside the insulation, which impacts the linear relationship. Linearity also helps to increase the validation of the method and that calculations are performed correctly. Equation 20 is used to calculate the dielectric loss factor. Assuming perfect linearity, a doubling in voltage and doubling in current will cancel each other out, which is why voltage increase should not lead to an increase of tan δ. As mentioned in subsection 1.4 the literature concludes that the Hamon approximation performs better when the polarization currents are used. However both the polarization and depolarization currents will be used to investigate the dielectric losses, as depolarization currents are still considered satisfactory.

Figure 32-35 show the dielectric loss factor as a function of voltage for different temperatures on all bars. While Figure 36-39 shows the dielectric loss factor as a function of temperature for different voltages on all bars. The calculation was done at 10 minutes or $f = \frac{0.1}{600\ s} = 1.667 \cdot 10^{-4}\ Hz$.

From these figures it is observed that linearity is found in all the bars. The lines are more or less straight for the voltage dependent plots as expected. Showing that the dielectric loss factor is mainly dependent on the temperature of the measurement. There are some nonlinearity observed as well. This is also expected and can be caused by several reasons. One is the uncertainty and wrongful measured currents from lower voltage and temperature tests, particularly clear in Figure 33. Another is natural differences from each time a test is conducted or the small difference caused by not fully discharging the bar before the next test. Both the semi-conductive paint and field grading may also impact the linearity [18], [19]. Since the guard will remove most, if not all of these currents, they are most likely not impacting in any significance. It is important to note that as shown in Figure 15, the guard is placed about 1 cm on the field grading in order to ensure the correct measurement area. This small area of field grading included in the measurement area may impact this linearity. Based on previous results it is also believed that some voltage dependency is caused by increased accuracy of the megger due to the increased current. As seen from the voltage dependent plots, the non linearity are not of much significance for analysis purposes. The two coatings impact are also more significant when testing with a full bar and not just the straight section as done in this thesis. It is important to be aware of these impacts, a guard should be used if testing is to be done on the main insulation only.

The dielectric loss factor is highly dependent on which temperature the test is conducted on. From $20^\circ - 130^\circ\ C$ the loss factor can vary from less than 1 to just below 100. It is therefore important to establish a base line of expected loss factor at certain temperatures in order to make any use of the data for condition assessment. The loss factor will also be dependent on the time or frequency the calculation is made at. Calculations were also made at different frequencies, where all plots were more or less identical in shape, only with difference being the calculated loss factor. In other words, for all frequencies the trends were the same and therefore only the 10 minute results are presented.

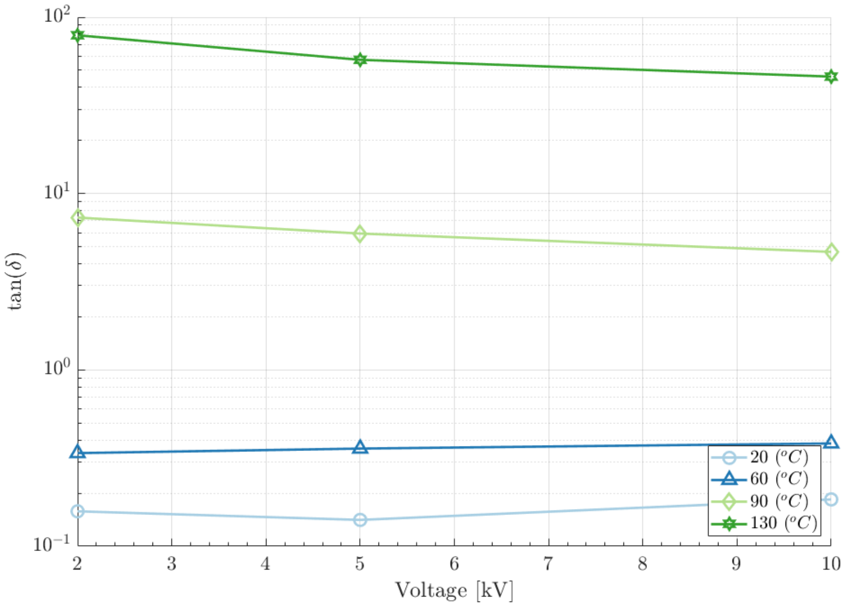


Figure 32: Dielectric loss factor tan (δ) of bar O117B as a function of voltage for different temperatures. Calculated for t = 10 minutes.

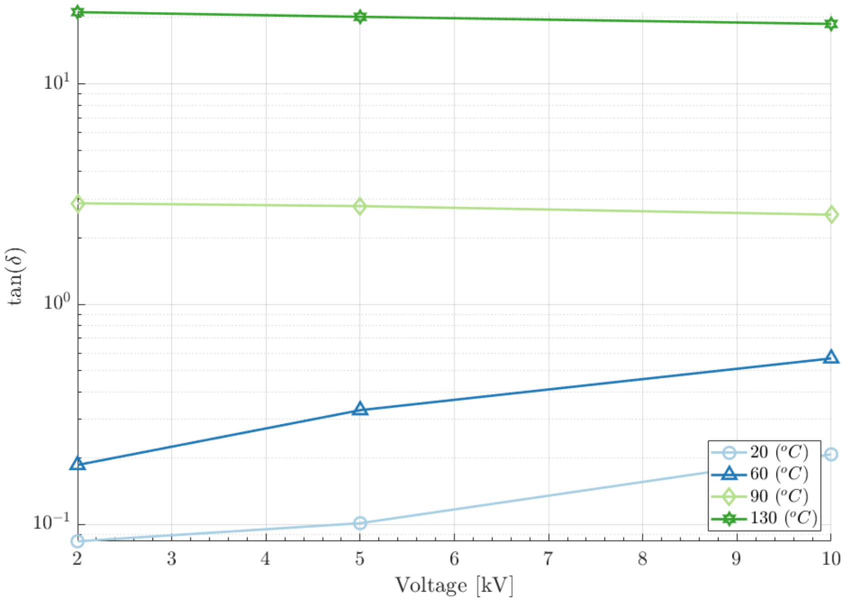


Figure 33: Dielectric loss factor tan (δ) of bar O120B as a function of voltage for different temperatures. Calculated for t = 10 minutes.

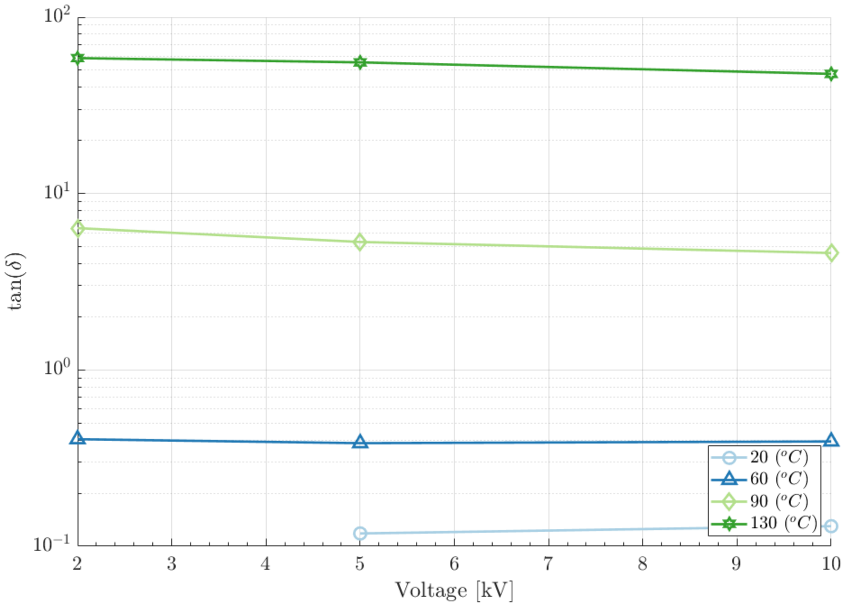


Figure 34: Dielectric loss factor $\tan(\delta)$ of bar O162B as a function of voltage for different temperatures. Calculated for t = 10 minutes.

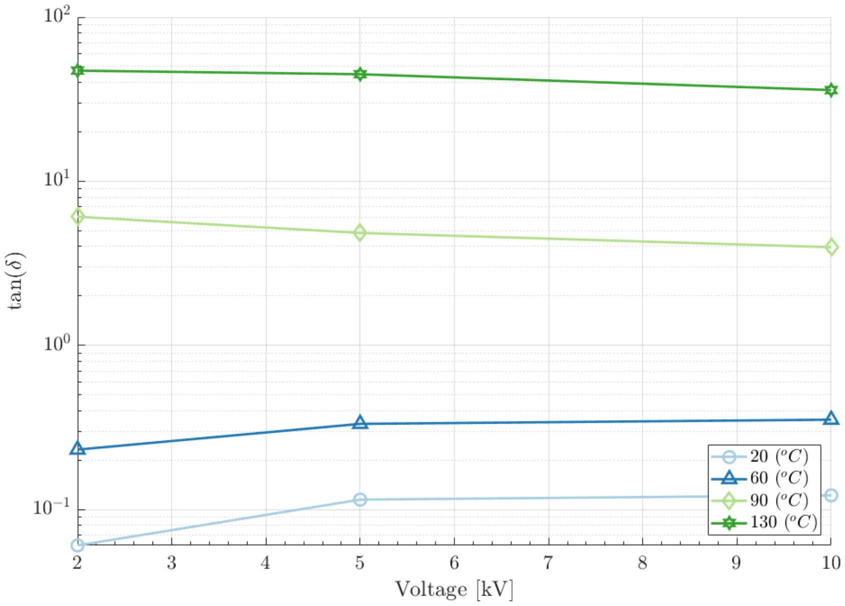


Figure 35: Dielectric loss factor $\tan(\delta)$ of bar O163B as a function of voltage for different temperatures. Calculated for t = 10 minutes.

From the temperature dependent plots in Figure 36 - 39 it is clear that the different bars show quite similar slopes as the temperature increases. It is observed that the bars do not have a perfectly linear relationship with the temperature as the slopes steepness varies between temperatures. The 10 kV tests is found to be the most linear tests, as expected due to them being more accurate. It is also clear that the 20 °C tests are the least similar to the other temperatures, providing more evidence to the issues when testing on that temperature.

It is again observed that some bars shows some voltage dependence. If the tests yielded perfectly linear results, all curves would be placed on top of another. While some voltages show more close results, especially at the higher temperatures, others have a bit more variations. O120B and O162B have the least variations between the voltages. If there are other causes of the non-linearities it is difficult to determine due to a lack of repeat testing under identical cases. Without base values of unaged bars it is also not possible to determine if some deviation from linearities are caused by deterioration. With access to those numbers correlations between non linearities and deterioration can be made in further work on the subject.

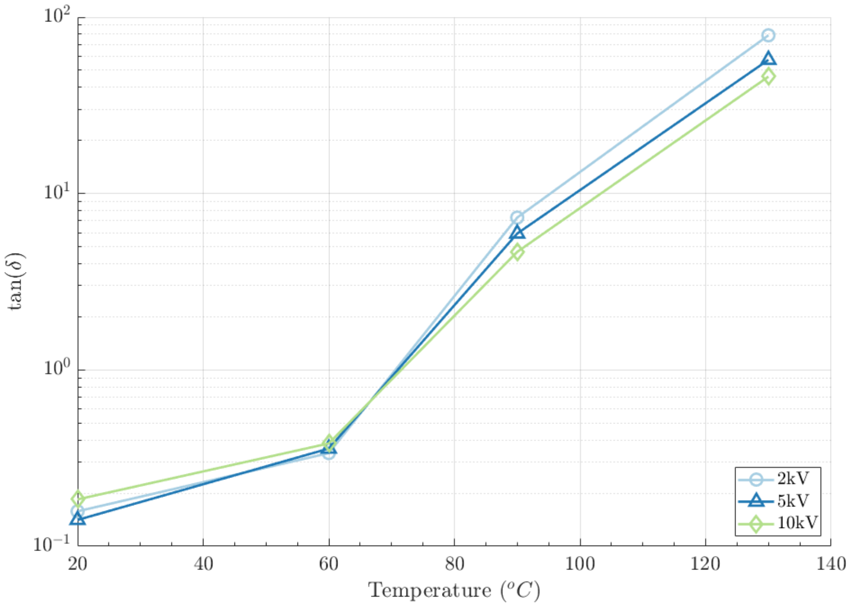


Figure 36: Dielectric loss factor $\tan(\delta)$ of bar O117B as a function of temperature for different voltages. Calculated for t = 10 minutes.

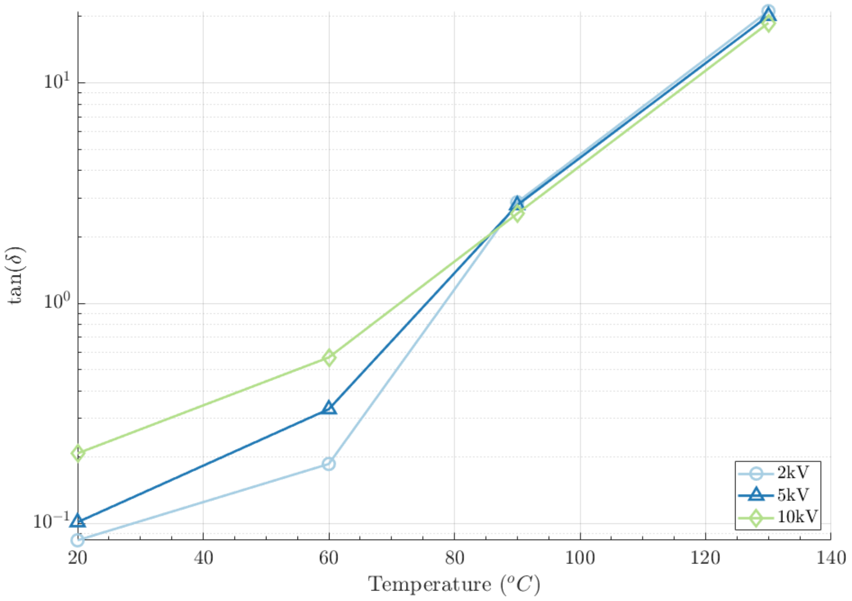


Figure 37: Dielectric loss factor $\tan(\delta)$ of bar O120B as a function of temperature for different voltages. Calculated for t = 10 minutes.

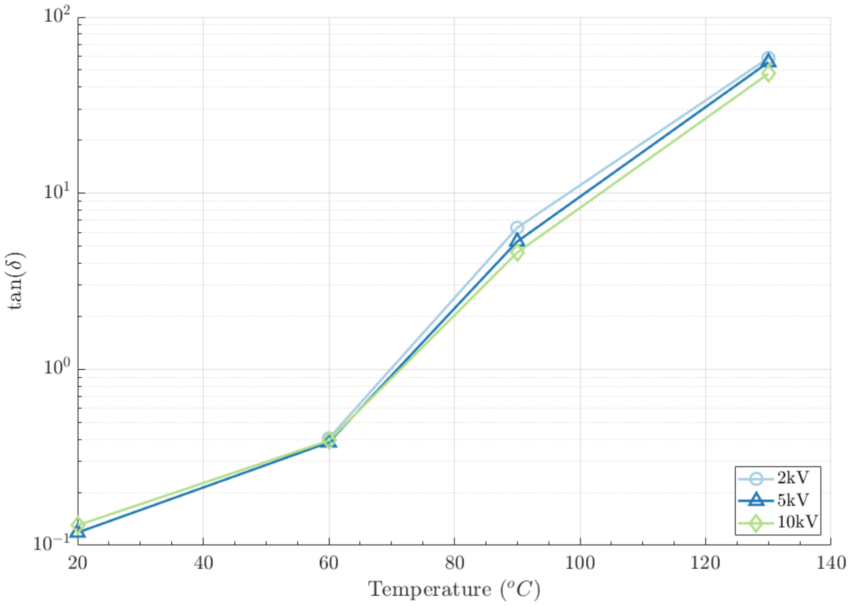


Figure 38: Dielectric loss factor $\tan(\delta)$ of bar O162B as a function of temperature for different voltages. Calculated for t = 10 minutes.

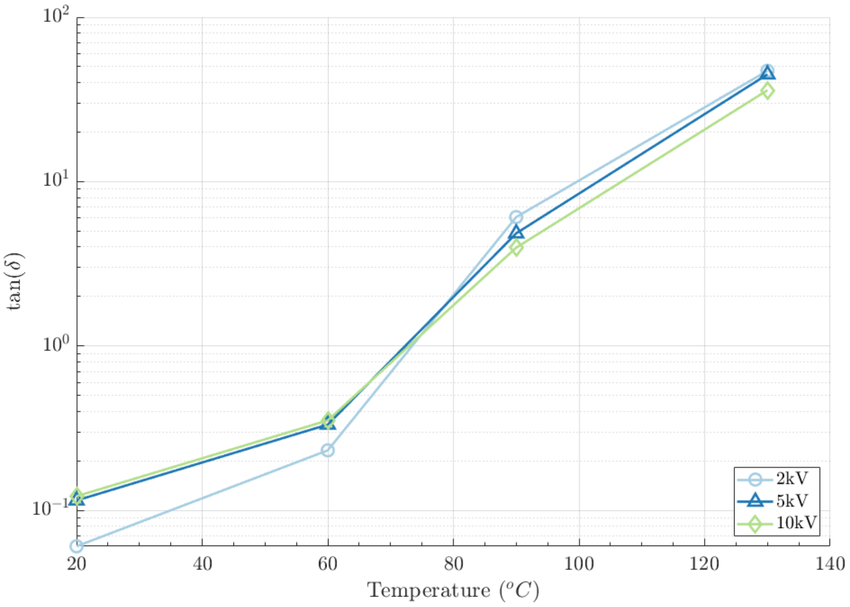


Figure 39: Dielectric loss factor $\tan(\delta)$ of bar O163B as a function of temperature for different voltages. Calculated for t = 10 minutes.

3.3.2 Dielectric loss factor as a function of time/frequency

Figure 40 - 44 shows the dielectric loss factor plotted as a function of frequency. As explained in subsection 1.5, the frequency is given by $f = \frac{0.1}{t}$. The polarization current has been used in the Hamon approximation for these plots. It is observed that for the lower temperatures that the largest value of the loss factor is found higher at frequencies. Meaning the contribution from polarization, in particular the delta part of the polarization current, is dominating the dielectric losses. As the temperature increases, the highest *tan* δ values occurs at the lowest frequencies. As seen from Equation 18, for high frequencies and high temperatures, the DC contribution will far exceed the polarization contribution, given the increased conductivity, which is now observed in the plots. This is also the explanation for the significantly high $\tan\delta$ values of up to 120 at some 130 °C tests. It is more common in literature to find *tan* δ values lower than 1. Either because the testing was on lower temperatures, or temperature correction has been used for the insulation resistance. With the exception of the higher values, the plots show similarities to those found in literature [13], [16].

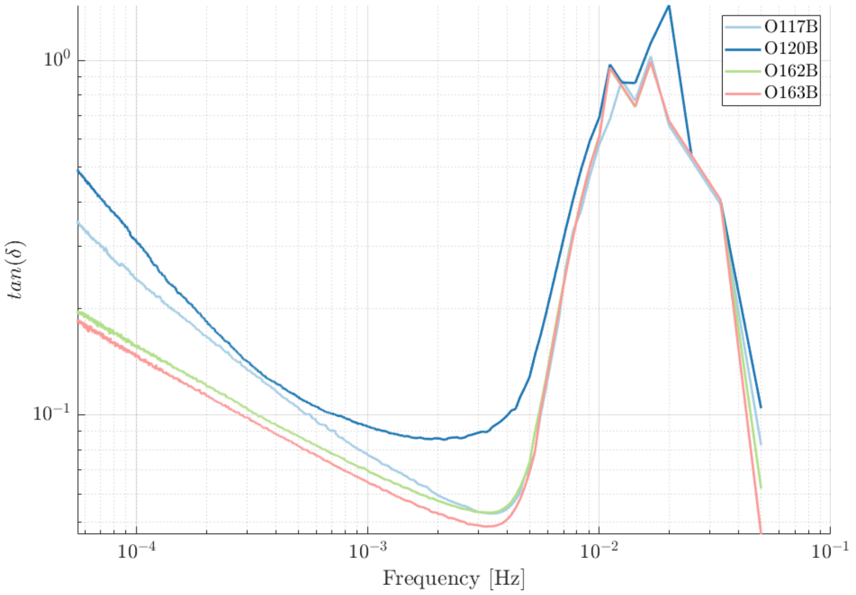


Figure 40: Dielectric loss factor $\tan(\delta)$ as a function of frequency for all bars at 20 °C 10 kV with the use of polarization current. As with the pol/depol plots and the DC plots this tests breaks with the trends as O120B has the highest dielectric loss. O162B which in most cases has the highest loss is now one of the plots with the least losses.

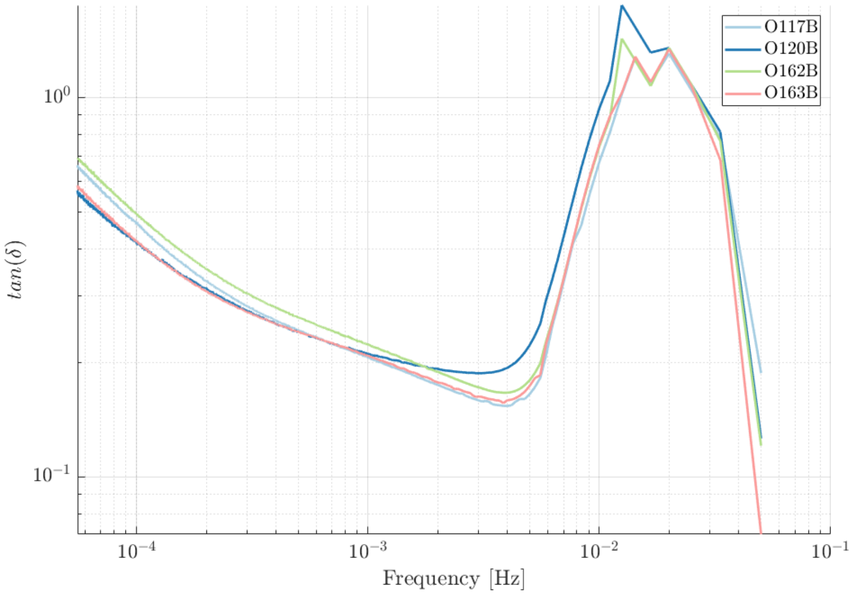


Figure 41: Dielectric loss factor tan (δ) as a function of frequency for all bars at 60 °C 5 kV, with the use of polarization current. On lower temperatures the highest loss factor values occur early in the test course as the contribution from polarization is greater than the DC contribution.

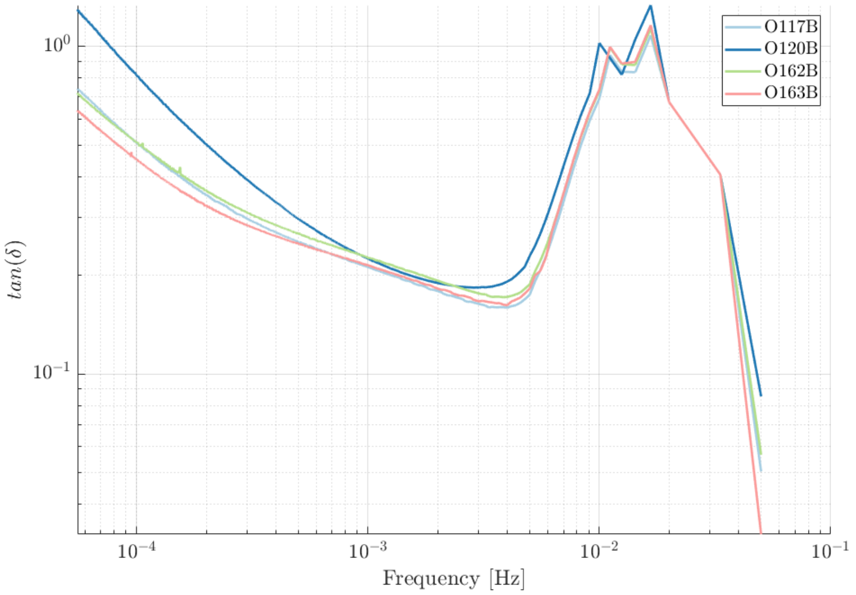


Figure 42: Dielectric loss factor $\tan(\delta)$ as a function of frequency for all bars at 60 °C 10 kV with the use of polarization current. The other tests case that breaks with the trends as O120B has the highest dielectric loss.

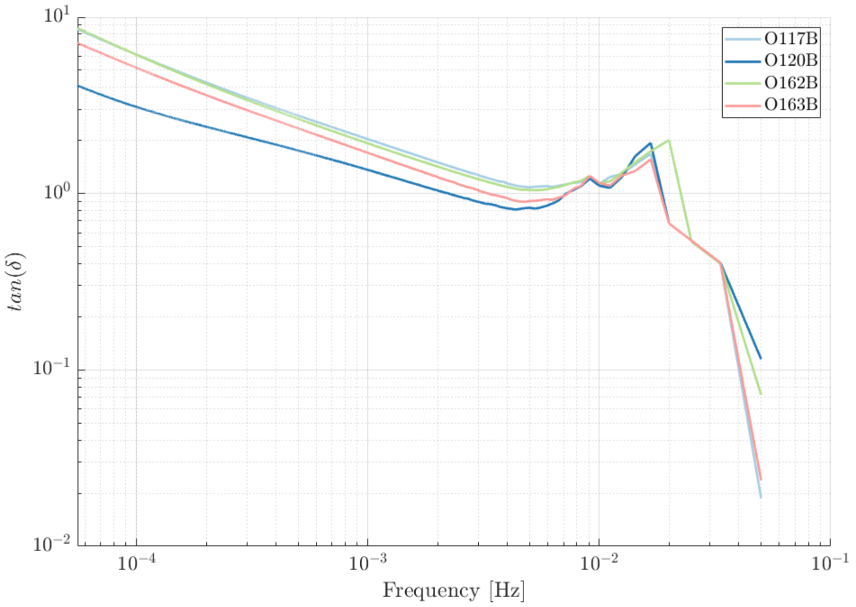


Figure 43: Dielectric loss factor $\tan(\delta)$ as a function of frequency for all bars at 90 °C 10 kV with the use of polarization current. As the temperature is increasing the highest loss factor values are found at the lowest frequencies. The DC contribution is far exceeding the polarization contribution.

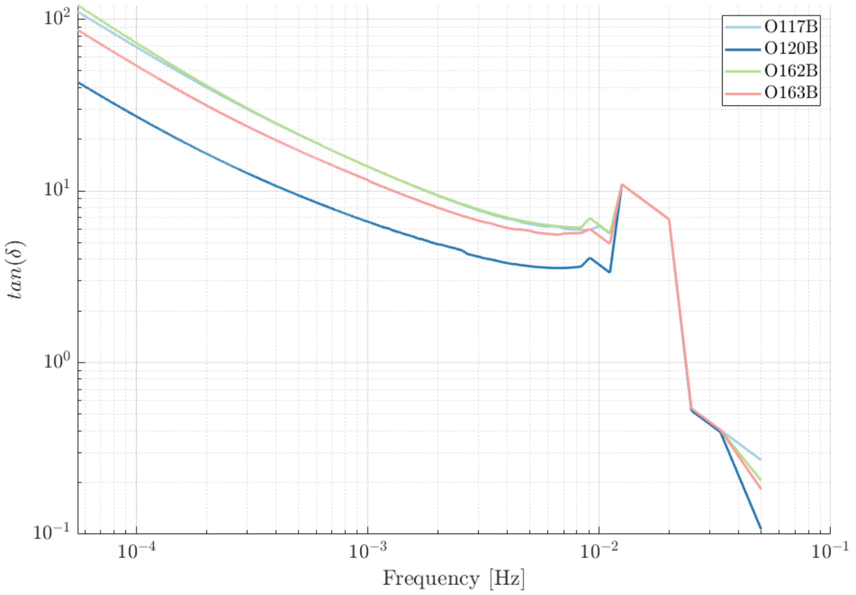


Figure 44: Dielectric loss factor tan (δ) as a function of frequency for all bars at 130 °C 10 kV with the use of polarization current. The trends for the bars performance is clear for all tests on 90 °C and above. O120B has the lowest losses, followed by O163B, O117B and finally O162B.

Even though it is considered less accurate [11], the depolarization current can still be used in the Hamon approximation and give satisfactory results [13]. Figure 45 - 48 shows plots of the dielectric loss factor as a function of frequency were the depolarization current has been used. In these cases, the loss factor has a much lower value. With the highest being Bar O162B at the lowest frequency ($5.56 \cdot 10^{-5}$ Hz or 30 minutes) and 130° C. Reaching 10.83 as opposed to 116 with the use of polarization on the same temperature and frequency. It is then clear that the DC component of the current during the polarization time will have the greatest contribution to the dielectric losses. This is expected as the DC component is extremely dependent on both temperature and frequency. It is also seen from the plots that even though there is no DC current contribution when using the depolarization current, the dielectric losses for depolarization are also impacted by the temperature. Which was also found to be true in [13].

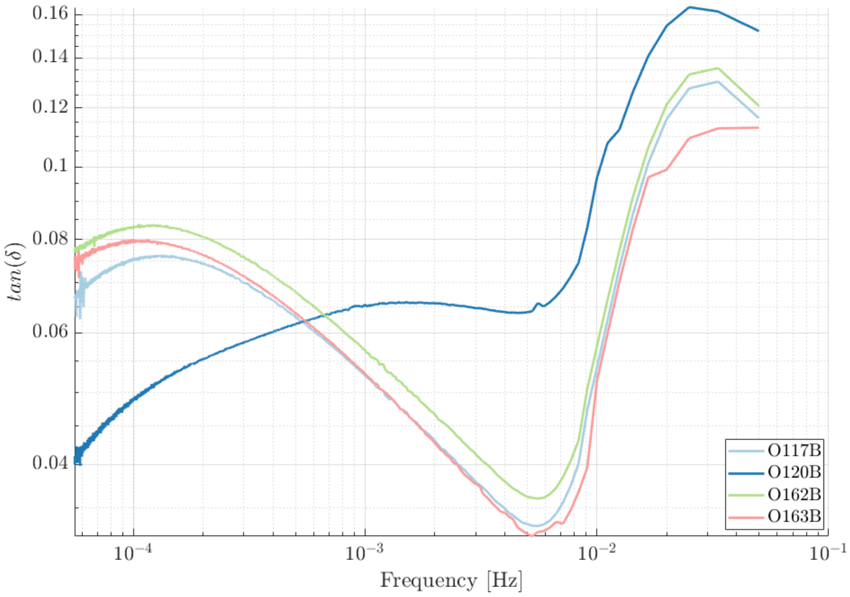


Figure 45: Dielectric loss factor $\tan(\delta)$ as a function of frequency for all bars at 20°C 10 kV with the use of depolarization current. O120B has the opposite results as when using polarization current with the lowest loss factor towards the end of the test course. The plots deviation inf form from the other bars may indicate test anomaly or incorrect measurement.

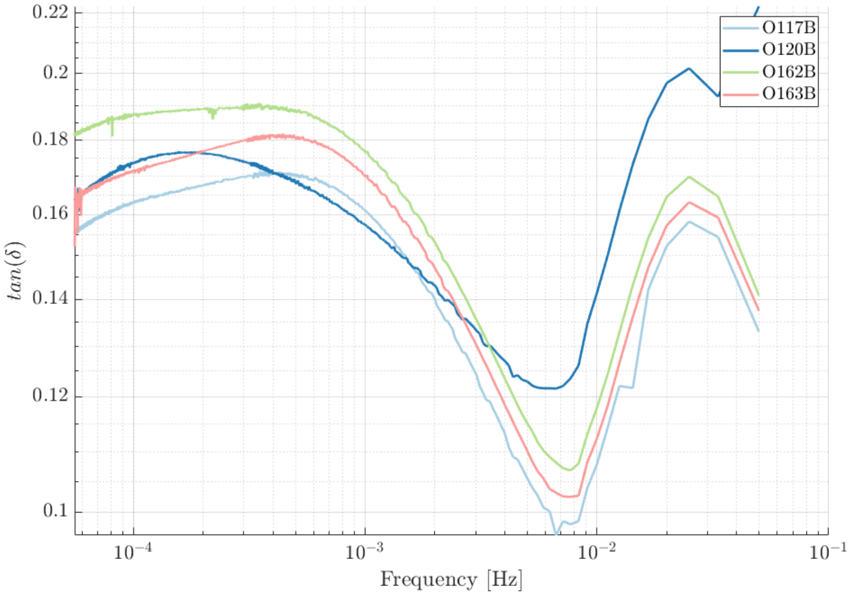


Figure 46: Dielectric loss factor $\tan(\delta)$ as a function of frequency for all bars at 60 °C 10 kV with the use of depolarization current. The other case where deviation from the trend is observed. O120B is more similar to the other bars in from. It has some strange behavior making it difficult to estimate if it has the third or second highest dielectric loss over the test course. Both O117B and O163B also has their positions changed in these tests which was not the case for polarization current.

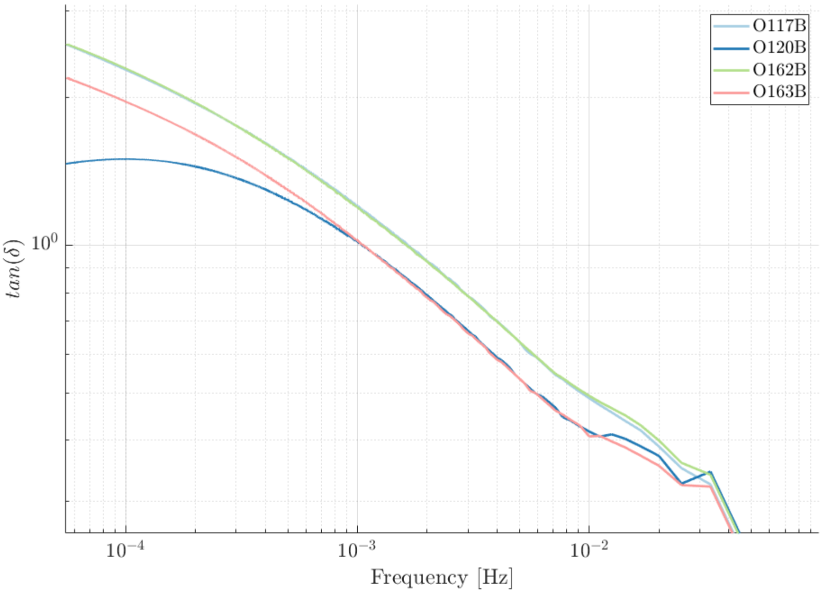


Figure 47: Dielectric loss factor $\tan(\delta)$ as a function of frequency for all bars at 90 °C 10 kV with the use of depolarization current.

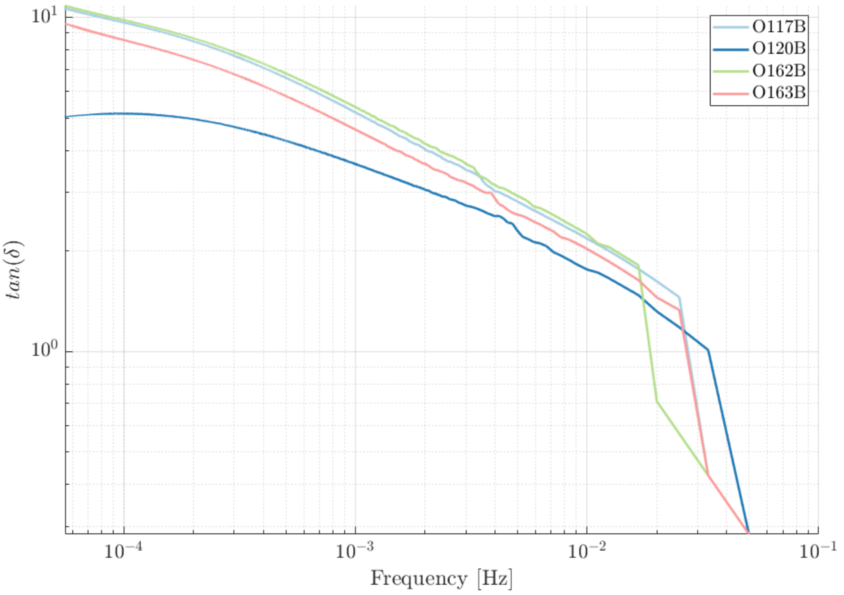


Figure 48: Dielectric loss factor $\tan(\delta)$ as a function of frequency for all bars at 130 °C 10 kV with the use of depolarization current. With higher currents from the higher temperatures the plots show the same trends as when polarization current was used.

For all measurements on 90° & 130° C the bars have consistent performance. With bar O120B having the lowest dielectric loss, followed by O163B and finally O162B and O117B with the highest loss. Just as with the measured currents, O162B and O117B are close in losses and interchanges during the test course. This trend is clear both when polarization and depolarization current is used for calculations. The fact that this trend persists for the the more credible tests, given the higher currents, it is reasonable to assume the bars have a difference in deterioration and the megger is able to detect this. The exception to the trend is the two anomaly cases at 20 and 60 °C 10 kV. By comparing the loss factor plots when polarization current is used to those with depolarization (Figure 40 to 45 and Figure 42 to 46). It is observed that that O120Bs $\tan\delta$ is not the highest when using the depolarization current for calculations. This shows that O120B has lower polarization contribution to its losses than some of the other bars in the two cases where it has the highest when polarization current is used. This observations makes it hard to determine the actual cause of O120B's behavior. It is also observed at the 20 °C that O162B which for the most part has the highest or second highest losses now has the second lowest when polarization current is used and still the most when depolarization is used. The 20 °C test hints at an anomaly when depolarization is used given that the plots shape is not similar to the other bars and the other O120B plots. While the 60 °C test does not deviate that much from the other bars in form. For both polarization and depolarization current it is clear results on 20 and 60 °C 10 kV deviate from the clear trend observed in the other tests. This, combined with the observation from the current tests that the megger show a significant amount of variations accuracy in test results, it is most likely an anomaly causing this behavior.

The calculation of dielectric loss factor can give good indicators on a components deterioration. The information is however not of much use unless a baseline has been established. Both a baseline from a more accurate test setup, which would help determine how accurate the megger is and a baseline from unaged bars. Data from unaged bars could help determining if the bars always behave more varying on lower temperatures because of low current or if it caused by the megger or the bars deterioration. Meaning the manufacturers of the components must begin with low frequency measurement of $\tan\delta$ so the expected values of unaged bars can be known. The other potential way is that each individual utility must do these measurements before the components begin operations. That way the utilities know exactly what is expected when conducting condition assessments with dielectric response. The megger does appear able to find accurate values for calculations of dielectric loss, as long as the current is high enough. There is also clear that some issues occurs when using the meggers results to develop dielectric loss plots. There are several anomalies or bars behavior who's cause could not be found. Only educated guess could be made, with the most likely being that it is just anomalies (incorrect measurements from the megger). No clear conclusion on the bars condition can either be determined without more repeat testing under same conditions.

3.4 Conductivity

As discussed above, the dielectric losses can be dominated by the DC contribution. This contribution arises from the bars conductivity, which is also a good indicator of a components condition. In reality it is difficult to distinguish between the losses caused by polarization and the conductivity [4]. Particularly for AC testing which is the most common for manufacturers. It is therefore more common to just use the dielectric loss tan δ either in frequency domain or with the Hamon approximation. Based on Equation 8 the DC conductivity is plotted and compared to the dielectric loss measurements.

3.4.1 Conductivity as a function of voltage and temperature

In Figure 49 - 52, the conductivity is plotted as a function of voltage for the different temperatures on the bars. Figure 53 - 56 shows the conductivity as a function of temperature for different voltages on all bars. If the conductivity plots are compared to the dielectric loss plots of the same bars, it is possible to observe significant similarities. The shape and slopes of the different plots are almost identical to the dielectric loss plots. Meaning that linearity can also be observed from the conductivity plots. Just as with the dielectric losses, the conductivity has almost no voltage dependency and is mostly dependent on the temperature. There is again also observed some small non linearity, which is as expected. Once more it is difficult to determine the reason for the non linearity. For the most part it is observed that the 10 kV tests are the most linear in the temperature dependent plots, same as for the dielectric loss plots. Although voltage does not impact the conductivity in a large scale, the higher the voltage the more accurate the meggers measurements are, which leads to to the 10 kV plots showing the most linearity.

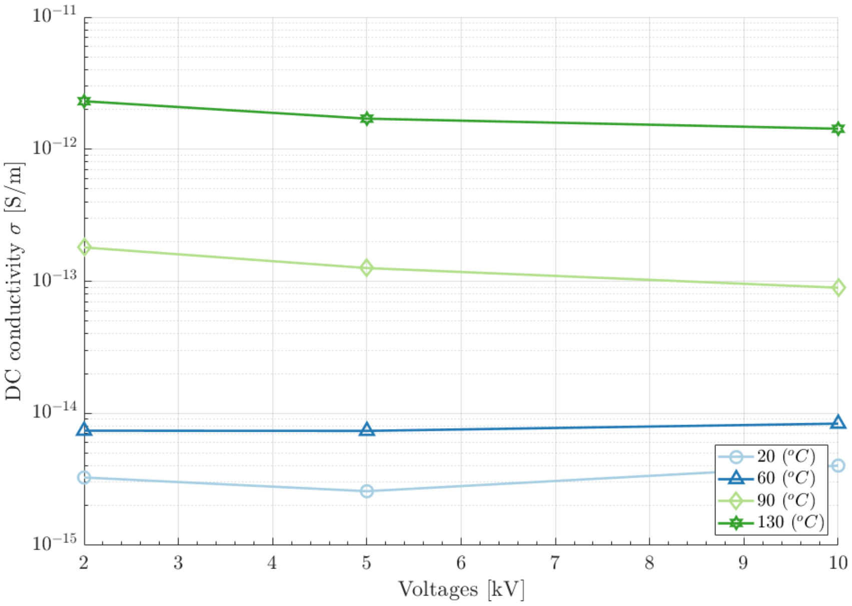


Figure 49: The DC conductivity σ as a function of voltage for the different temperatures on bar O117B.

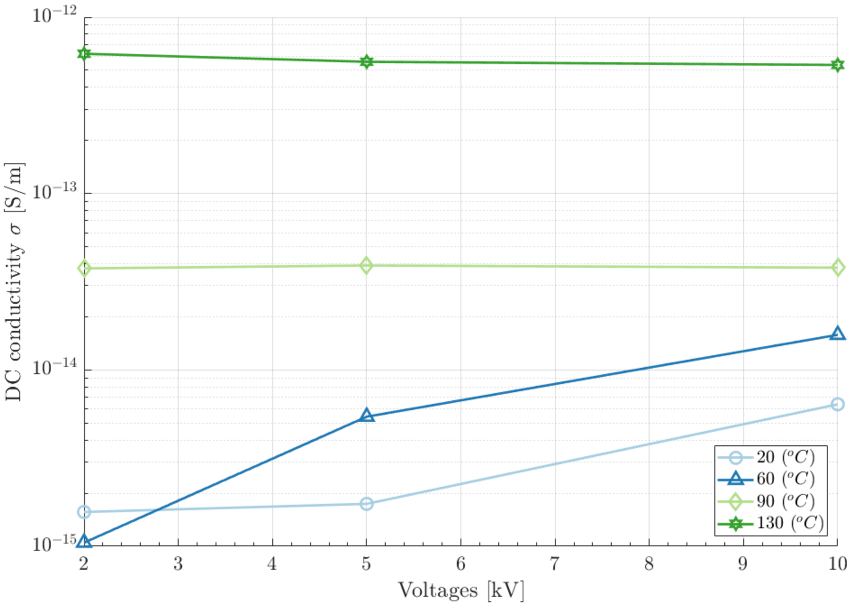


Figure 50: The DC conductivity σ as a function of voltage for the different temperatures on bar O120B.

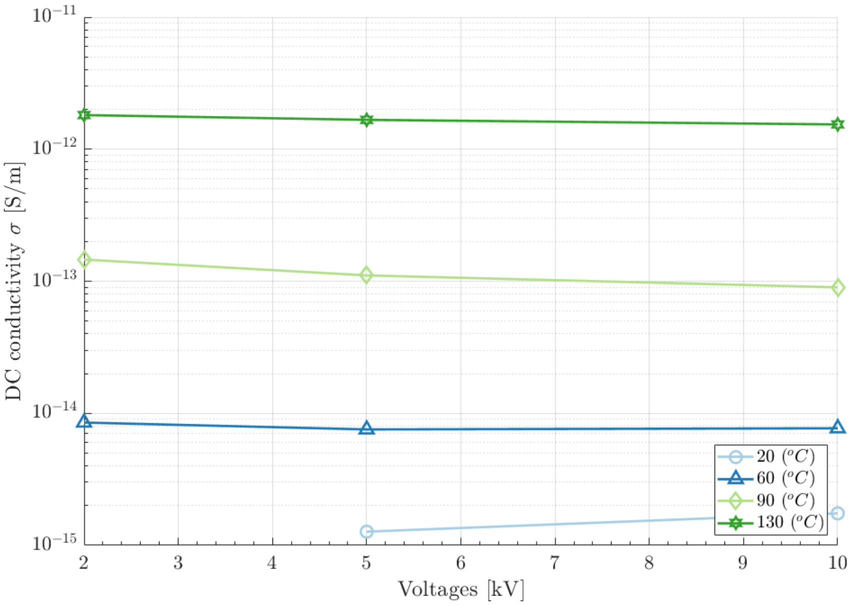


Figure 51: The DC conductivity σ as a function of voltage for the different temperatures on bar O162B.

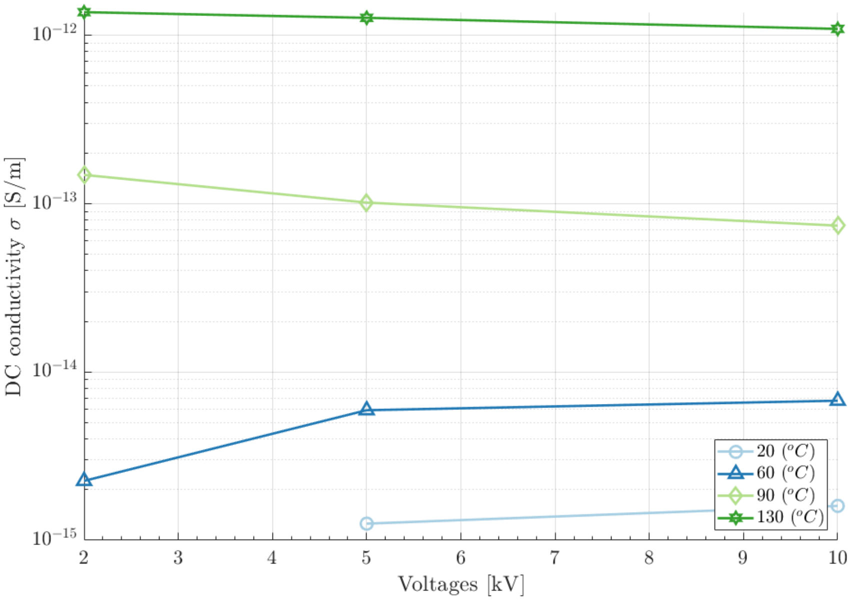


Figure 52: The DC conductivity σ as a function of voltage for the different temperatures on bar O163B.

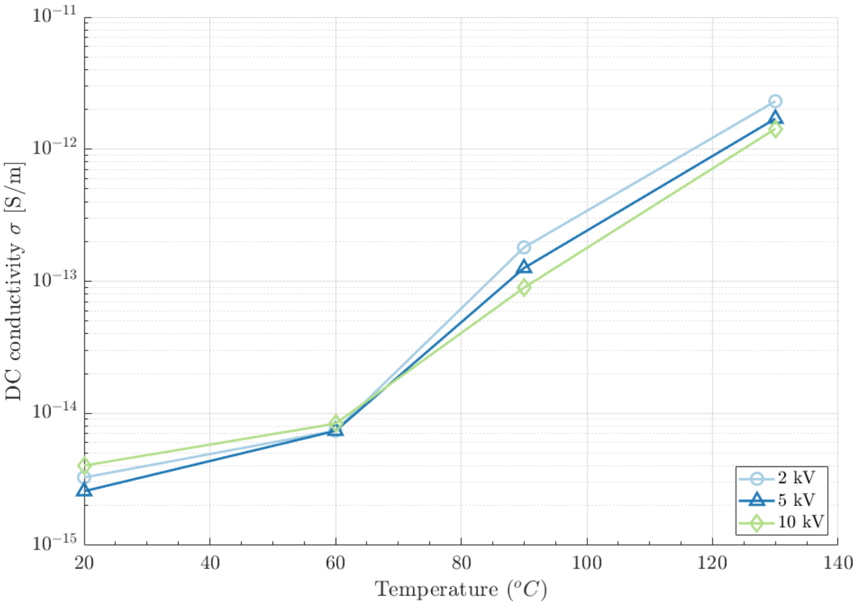


Figure 53: The DC conductivity σ as a function of temperature for the different voltages on bar O117B.

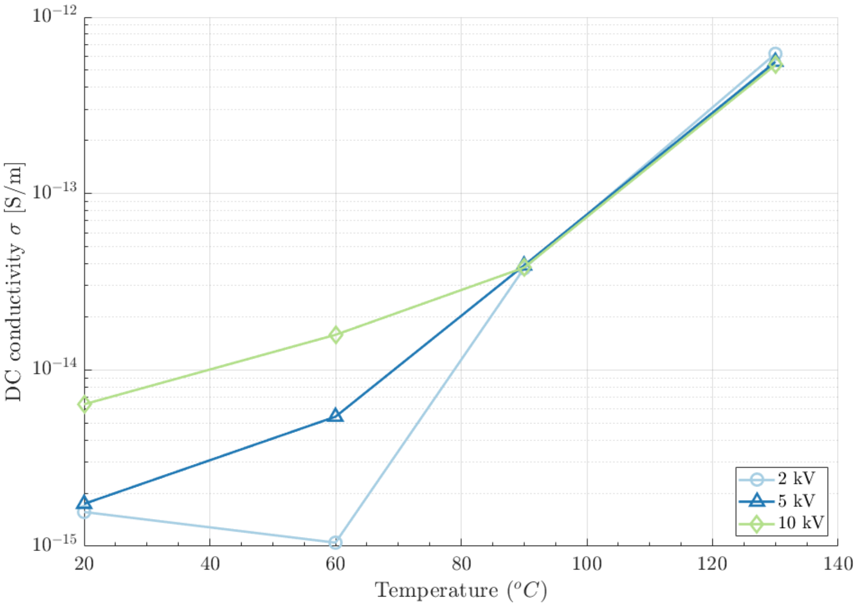


Figure 54: The DC conductivity σ as a function of temperature for the different voltages on bar O120B.

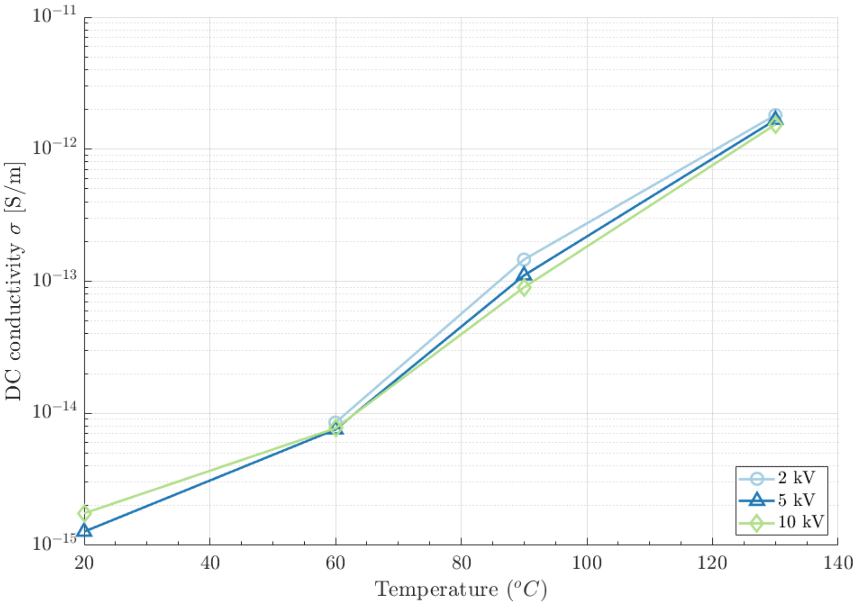


Figure 55: The DC conductivity σ as a function of temperature for the different voltages on bar O162B.

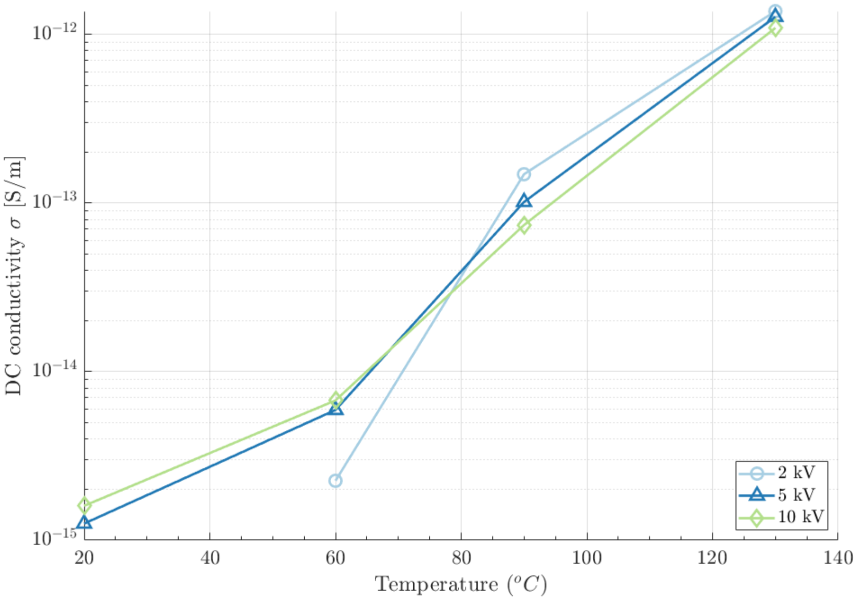


Figure 56: The DC conductivity σ as a function of temperature for the different voltages on bar O163B.

3.4.2 Conductivity as a function of time

Figure 57 - 60 shows the DC conductivity as a function of time. Comparing these with the DC plots in subsection 3.2, it is observed that the conductivity plots are fairly similar to the DC results. This is expected since the DC current is is solely based on the conductivity of the insulation. When comparing the conductivity with the dielectric losses as a function of frequency, it can also be observed that the lower the conductivity, the lower the dielectric loss as expected. The conductivity results coincides with the bars performance as discussed in subsection 3.3, dielectric loss. With O120B performing the best with the lowest conductivity followed by O163B, O162B and finally O117B for most cases. This observation holds true for the 90 ° and 130°C test where the accuracy of the megger is found to be the best. There is as expected more variations on the bars behavior, i.e which bar performs best with lowers current, on the lower temperature tests.

From the results it is also clear that the temperature is the greatest impact on conductivity. While a change in voltage may slightly impact the conductivity, the change is still within the same order of magnitude. While the temperature from 60° - 130° C increases by up to one thousand times. For these higher temperatures, the conductivity will be the dominant component to the dielectric losses, in particular on the lower frequencies. The clear correlation between conductivity and dielectric losses means that measuring the conductivity in aged bars and comparing to unaged is another viable method to investigate a insulators condition.

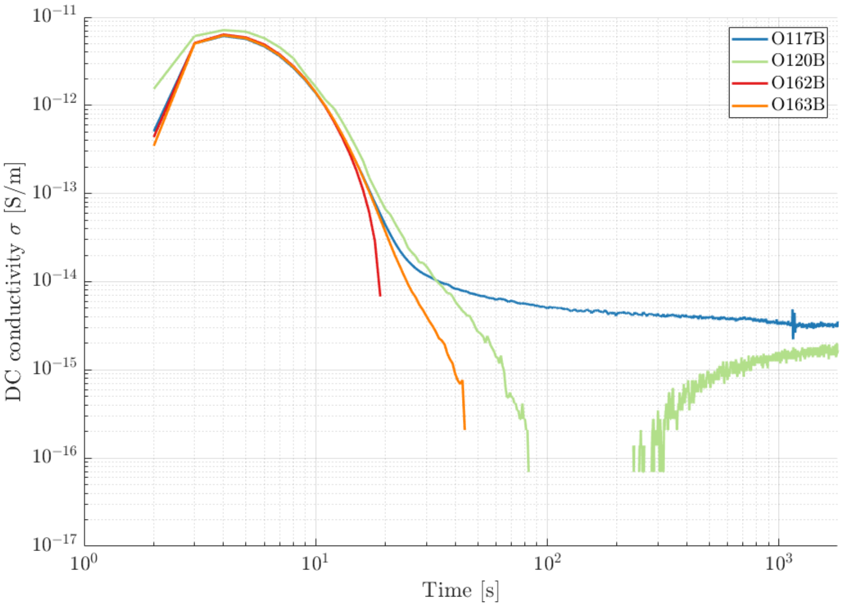


Figure 57: DC conductivity σ as a function of time for all bars at 20 °C 2 kV. Just ass with the DC plot under same condition the meggers incorrect measures are seen here as well.

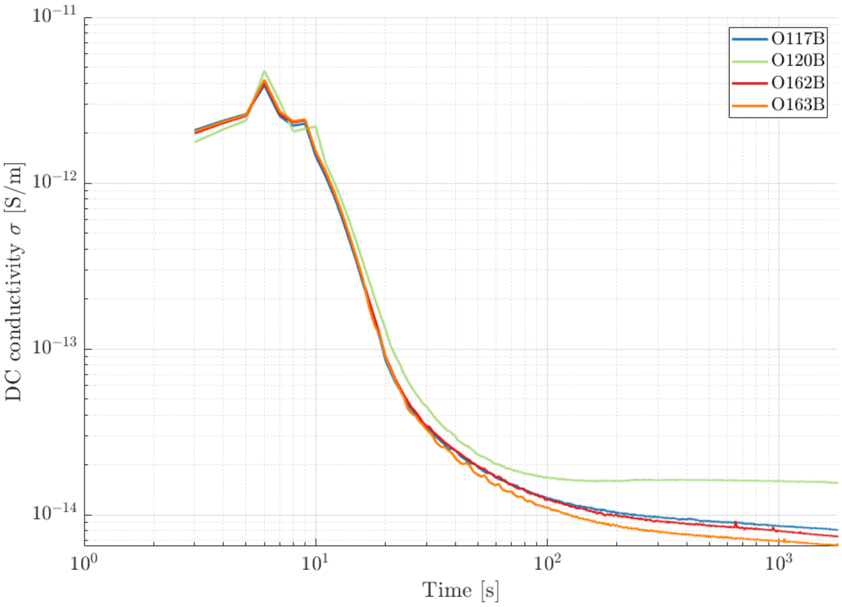


Figure 58: DC conductivity σ as a function of time for all bars at 60 °C 10 kV. The conductivity plots follow the DC plots closely, able to detect the deviation of O120B from trends as it has the highest conductivity for this test case.

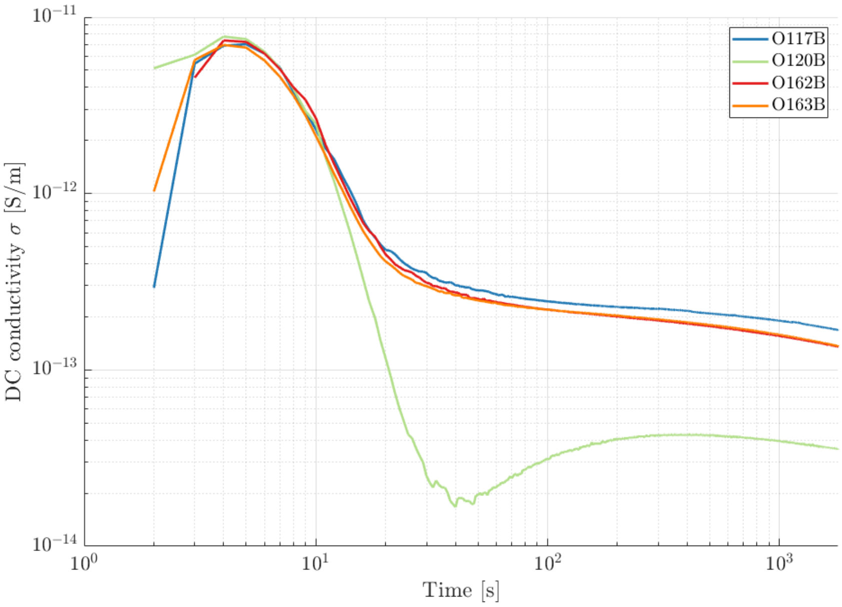


Figure 59: DC conductivity σ as a function of time for all bars at 90 °C 2 kV. The strange measurement of O120B shows the dip conductivity before increasing towards a flat stable area. This coincides with the observation of the DC current plot where the bar had negative DC current due to a brief moment of higher depolarization than polarization current.

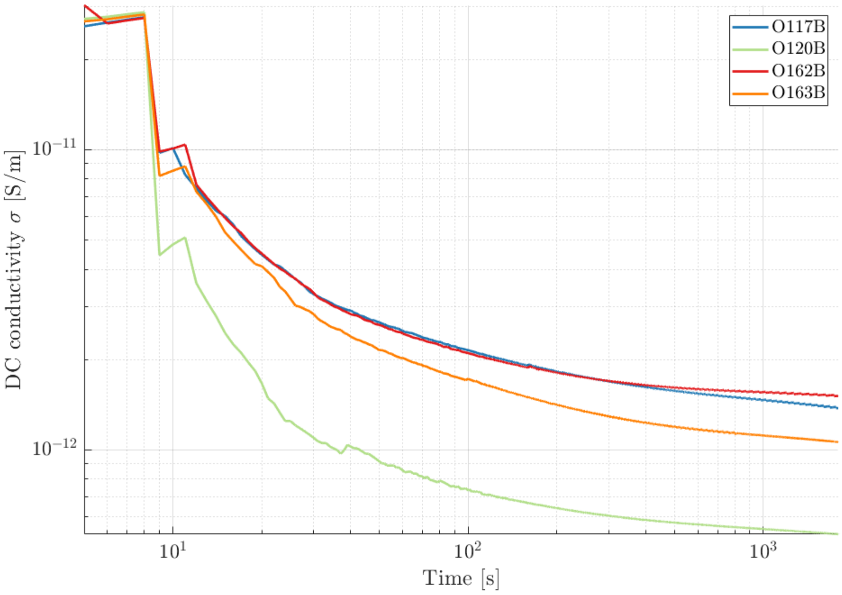


Figure 60: DC conductivity σ as a function of time for all bars at 130 °C 10 kV. The highest temperature and voltage produces again one of the more credible results with plots as expected from theory.

3.5 Comparison of tests before and after thermal cycling

Thermal cycling was conducted on three bars, where O163B were cycled 238 times and both O117B and O162B were cycled 208 times. O120B Could unfortunately not be thermally cycled due to delays caused by issues with the guard during the cycling as well a bad connection, which lead to the bars becoming too hot. The tests would be performed on the three remaining bars on the same temperatures and voltages in order to compare results. Before testing after the thermal begun, the hypothesis was that no significant difference would be detected. Based on the belief that the high stress in a short time would not cause a noticeable difference in the bars compared to the stress and potential deviation that almost 50 years of service would. Up until that point, the megger had been observed to show strange behavior and a fair amount of randomness in some of its tests that were fairly equal, so some normal variations from the megger were expected to be found.

3.5.1 Polarization and Depolarization currents

A comparison of polarization and depolarization currents before and after thermal cycling is presented in Figure 61 - 65.

The clear trend from the results are that both measured currents and shape of the plots are fairly close both before and after cycling. There are some exception such as for 20° C 2 kV

tests as expected from the inaccuracy of low currents. Figure 62 also show a strange drop in polarization current before increasing again. This is most likely a test anomaly as it breaks with all other trends for just this one test case. It is also found, as expected, that the higher voltage and temperature tests show the closest similarities before and after cycling. Each test also has some difference in measured current before and after cycling. For this however, there is no clear trend to observe. It is more or less random if a bar will have higher or lower current for a test after the cycling. This randomness indicates that the thermal cycling does not deteriorate the bar in any significant way that can be measured with the megger, and the difference is the natural variation from the megger. One bar may for instance have lower current on 2 and 5 kV tests while a higher current on the 10 kV test at the same temperatures. The difference before and after may vary from 4-5 % to just above 20 %. Whether this difference is lower or higher after the cycling seems random. The same bar can experience a 20 % increase after cycling on the 5 kV test only to have 5 % less current on the 10 kV test starting only an hour later. The difference in current is therefore more likely to be natural variations between each test which was constantly observed before cycling as well.

It is also observed that after cycling, one bar may have a higher current than the test before for polarization, while its depolarization current is the opposite. This observation in addition to the fact the depolarization currents show no significant deviation from the literature, gives more evidence to the idea that most of the measurement uncertainties occur in the polarization measurement part of the tests. The meggers calculation of insulation resistance when measure currents is what appears to cause issues. As for depolarization there are no resistance and no issues even for the lower currents other than some noise around 1 nA. Before and after cycling, the biggest differences in measured current are found in the polarization measurement. There are much smaller differences found for depolarization with the highest being about 10 % in one specific case with less than 5 % being more common. This also supports the theory that the resistance is causing the most problems when using a megger.

Whether the currents after cycling was higher or lower than before is found to be somewhat random. Most test cases show the trend of close results, especially the shape of the plot, with the magnitude differing. It is believed that cycling had no significant impact, and that they almost may be reviewed as repeat tests under the same conditions as before cycling. The most critical information obtained is then that the megger, even on higher temperatures and voltages may measure a rather significantly different current from one test to another.

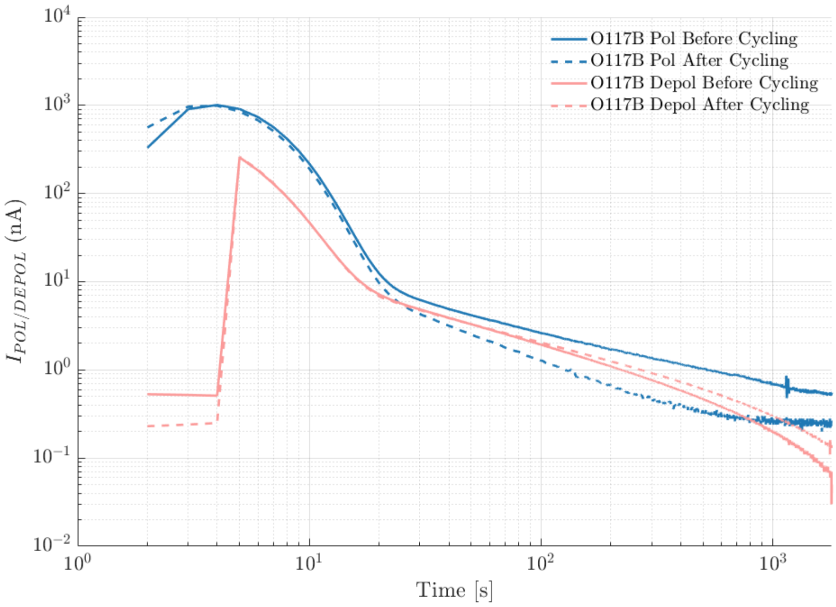


Figure 61: Polarization and Depolarization currents before and after thermal cycling for bar O117B at 20 °C 2 kV. An example showing that the problems on 20 ° test still persists. In this case the polarization current after cycling is lower than depolarization which will lead to a negative DC current. The opposite of what occured before cycling.

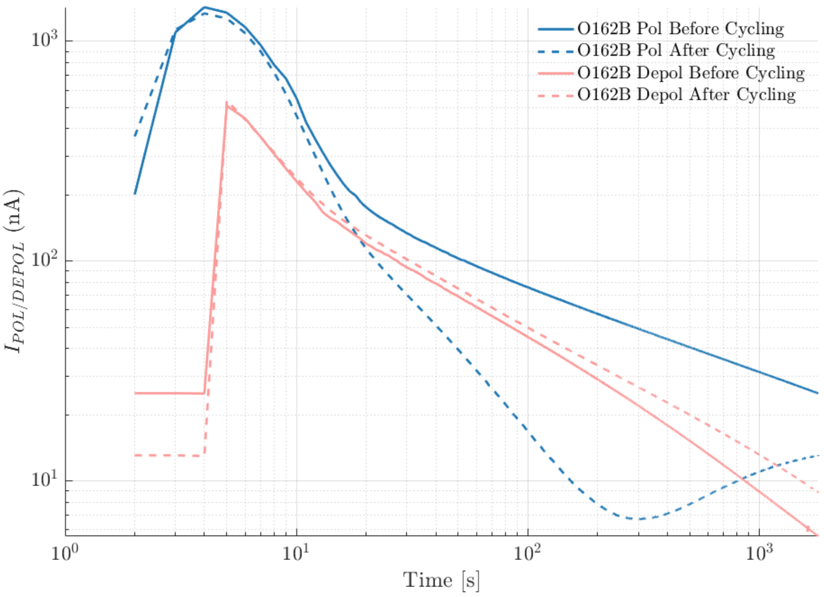


Figure 62: Polarization and Depolarization currents before and after thermal cycling for bar O162B at 90 °C 2 kV. Here it is observed that O162B after cycling has a rapid decrease in current before starting to increase at the end. It breaks with most trends, indicating that it most likely is an anomaly in the test.

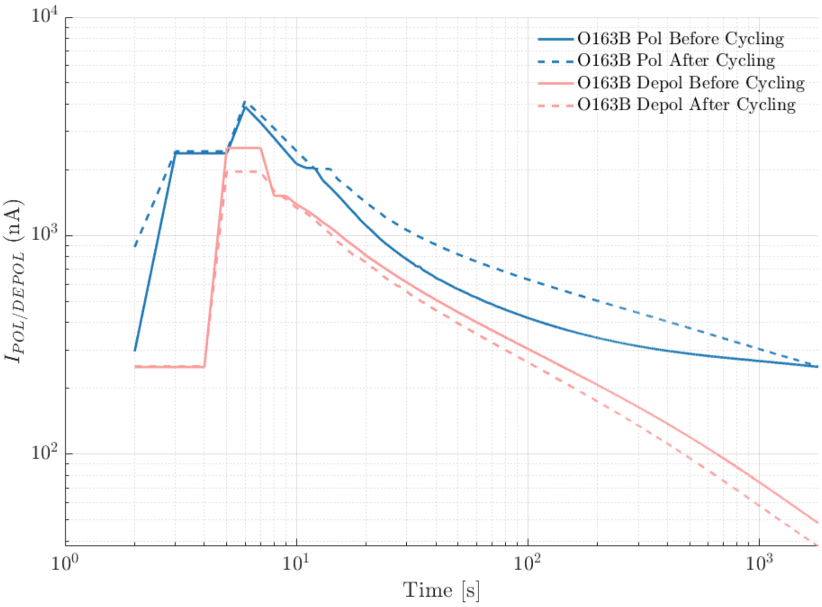


Figure 63: Polarization and Depolarization currents before and after thermal cycling for bar O163B at 130 °C 2 kV. The polarization current after cycling does not start to flat out as much as before cycling. One of the cases on higher temperatures and voltages that showed a bit more deviation after cycling than before.

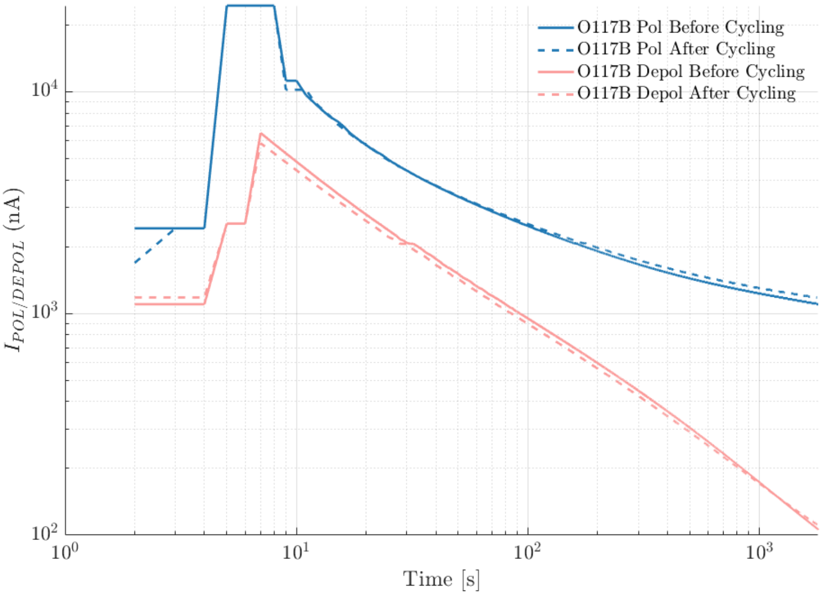


Figure 64: Polarization and Depolarization currents before and after thermal cycling for bar O117B at 130 °C 10 kV. Results are almost identical in shape with some difference in current magnitude. The currents after cycling stabilizes higher than before cycling.

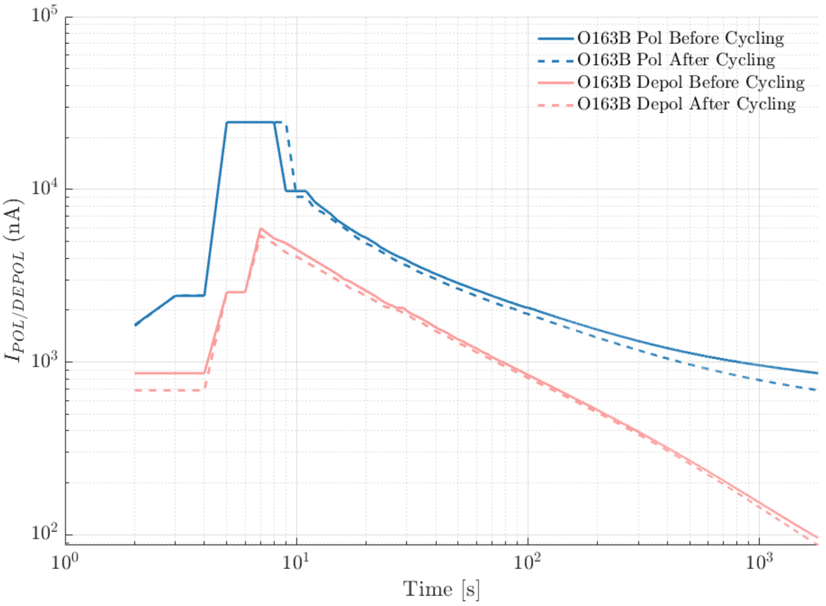


Figure 65: Polarization and Depolarization currents before and after thermal cycling for bar O163B at 130 °C 10 kV. As with the other 130 °C test the results are fairly close before and after cycling. It is observed in this test case that the current after cycling is lower than before, as opposed to the other bars on same temperature and voltage.

3.5.2 DC current

A comparison of the DC currents before and after thermal cycling for all the bars are presented in Figure 66 - 69. From these plots it is possible to observe the same trends before and after cycling. There are, as expected issues with 20 °C 2 kV tests again. For bar O163B, its DC current does not reach zero or negative numbers after cycling as opposed to before the cycling. In this case the the maximum resistance was reached after about 15 minutes instead of just above 5 minutes before cycling. Allowing the megger to more accurately estimate the current as seen by it flattening out more. The low current below 1 nA still causes significant variation/noise. For the same conditions, O117B had the opposite occur, where the test after cycling ending with negative DC as maximum resistance was reached after only 3 minutes. This gives more evidence to the meggers random behavior and uncertainty when measuring lower currents.

For the 90 and 130 °C tests, the results are fairly identical in plot shape. There are observed some significant differences in magnitude after the cycling. At 130 °C 10 kV for instance, bar O117B and O162 has a DC increase after 30 minute test of 80 and 120 nA respectively. While O163B has a decrease of 176 nA. This difference is almost entirely caused by the polarization current contribution, as there are small differences in depolarization between the tests. This could indicate an increase in conductivity caused by increased deterioration from thermal cycling. However the randomness of whether a test has higher or lower current after cycling makes it difficult to say for certain. It is instead believed that this shows the meggers uncertainty instead of detecting increased deterioration.

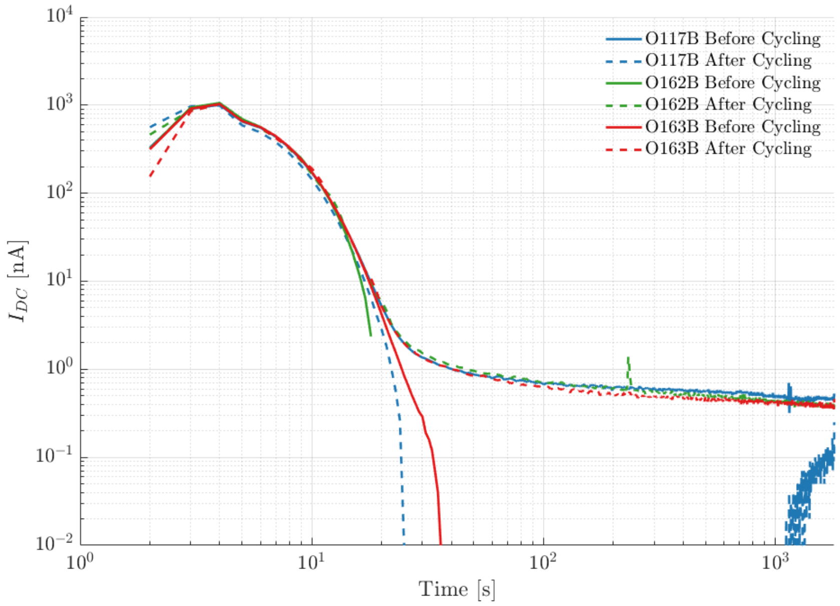


Figure 66: DC currents before and after thermal cycling for all bars at 20 °C 2 kV. O163B and O117B experienced opposite results after cycling. O163B had a negative DC current before cycling, while positive after. O117B had the opposite case with positive DC before cycling and negative after. O162B before cycling had problems conducting the test, so no comparison can be made.

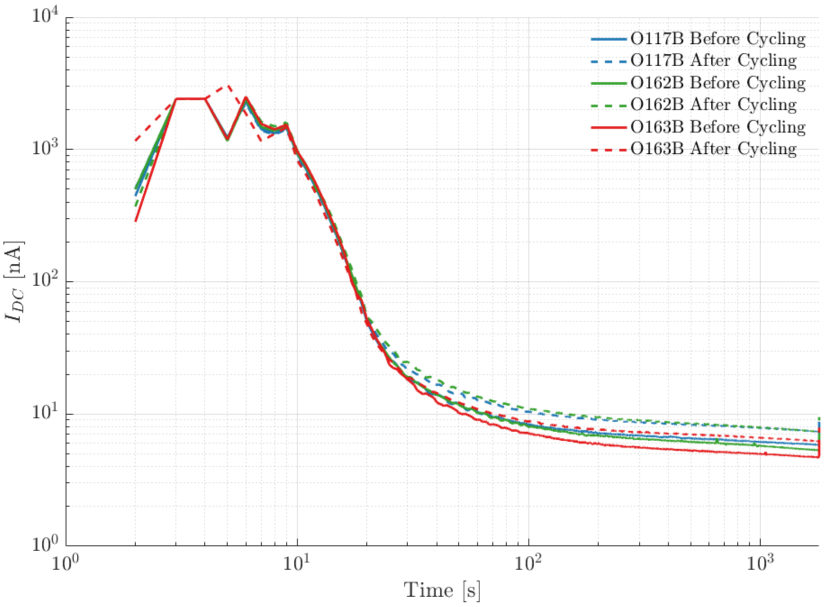


Figure 67: DC currents before and after thermal cycling for all bars at 60 °C 10 kV. The shape after cycling is fairly identical to before. The increased current magnitude of all results after cycling could indicate deterioration increase. However other plots contradicts this.

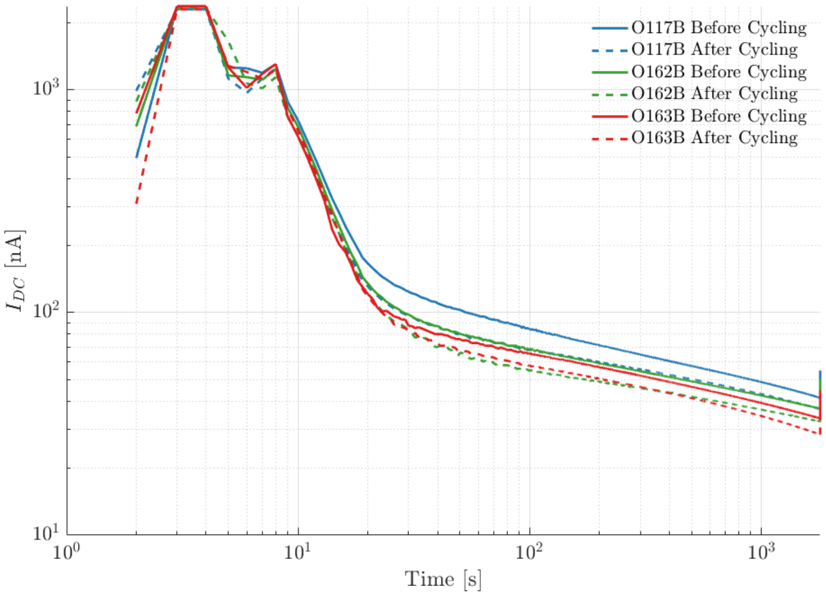


Figure 68: DC currents before and after thermal cycling for all bars at 90 °C 5 kV. The shape for all bars is close to identical before and after cycling, while the magnitude is different. All bars had lower currents after cycling than before. Making it difficult to determine if there is an increase in deterioration.

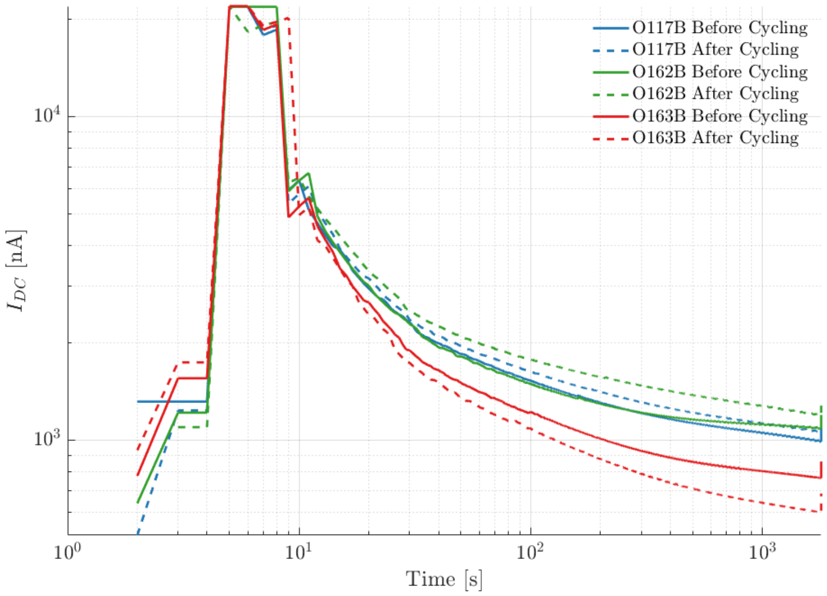


Figure 69: DC currents before and after thermal cycling for all bars at 130 ° C 10 kV. In this case only O163B had lower current after cycling than before, which again prevents clear trends of thermal cycling impact to be found.

3.5.3 Dielectric loss factor

Comparison of the dielectric loss factor before and after thermal cycling is presented in Figure 70 - 73. The results before and after cycling are more or less identical in shape with only the magnitude being different. Once more thermal cycling shows no significant impact on the the bars. As discussed in the previous sub sections, the natural variations from one test to another is believed to be the driving factor of the differences observed. Dielectric losses, as explained in subsection 3.3, is in theory mostly dependent on temperature. It is then observed for 130 °C 2 kV that bar O163B had higher losses after cycling, however at the same temperature with a voltage increase to 10 kV O163B has higher losses before the cycling. The tests therefore shows that there are rather significant variations when only the voltage is varying. This is only due to the meggers measurements not being perfect. As previously discussed there is a element of randomness as to whether a test will have higher or lower current after the thermal cycling. It is also observed the change from 60 - 90 °C. The losses goes from being greater after cycling at 60 °C to being lower after cycling at all 90 °C tests. The losses after cycling are then for the most part higher on 130 ° tests, with the exception of O163B on 5 and 10 kV tests. This shows the randomness of whether the current is higher or lower after cycling. Both 90 and 130 °C are the most credible tests and the two different temperatures show opposite trends after cycling. It is therefore difficult to establish a clear trend for the cycling impact on the losses. Which bar has the lowest losses are still the same after cycling as before. O163B performs best, followed by O162B and O117B. Just as before cycling, many tests have O162B and O117B so close and interchanging that its difficult to estimate which has the lowest loss as a function of time/ frequency.

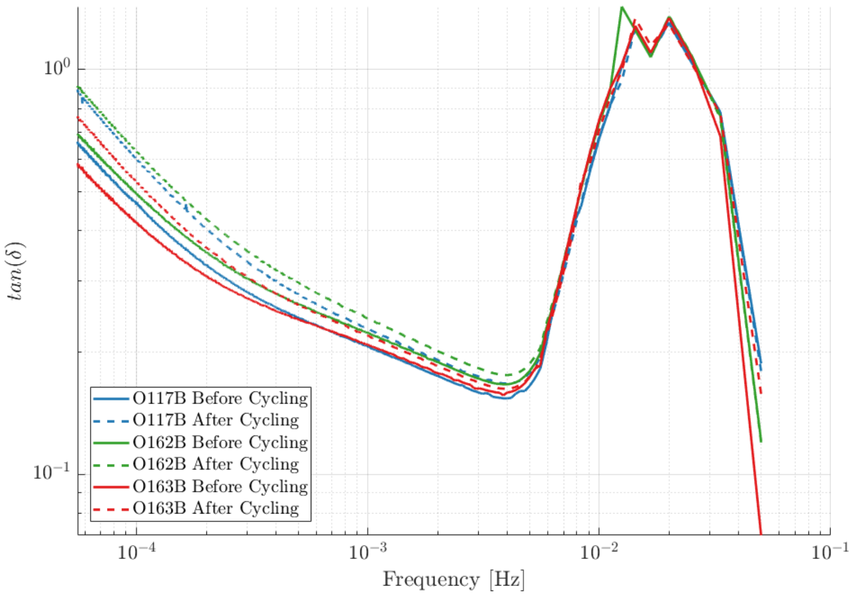


Figure 70: Dielectric loss factor tan δ before and after thermal cycling for all bars at 60 ° C 5 kV. With the use of polarization current for calculations. In these test all losses after cycling are higher than before.

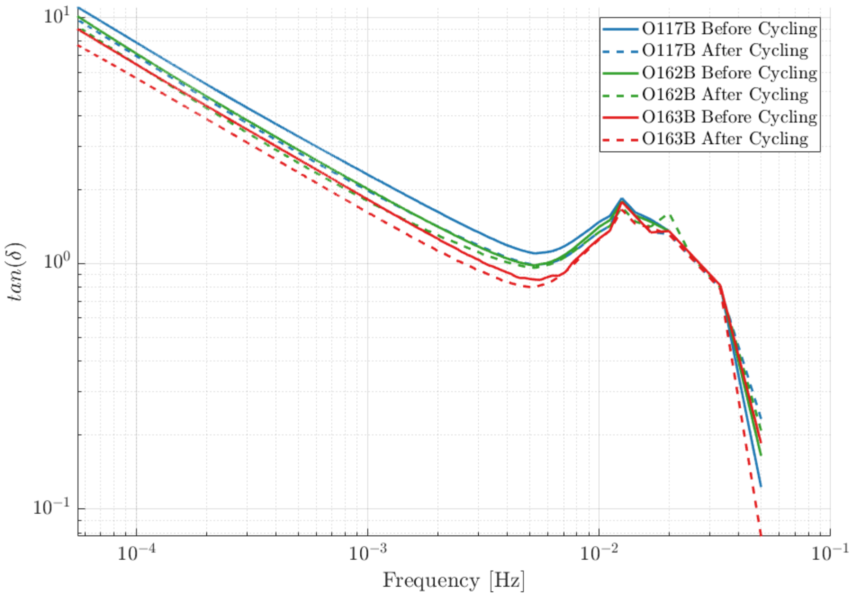


Figure 71: Dielectric loss factor $\tan\delta$ before and after thermal cycling for all bars at 90 °C 5 kV. With the use of polarization current for calculation. In these cases all losses after cycling were lower than before.

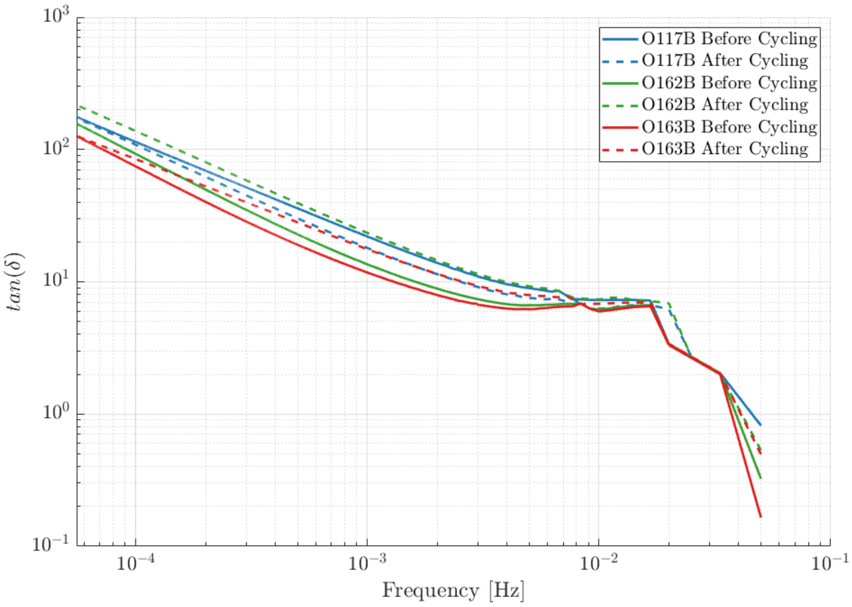


Figure 72: Dielectric loss factor $\tan\delta$ before and after thermal cycling for all bars at 130 °C 2 kV. With the use of polarization current for calculations. Here O163B and O162B had the highest losses after cycling, while O117B had lower after cycling.

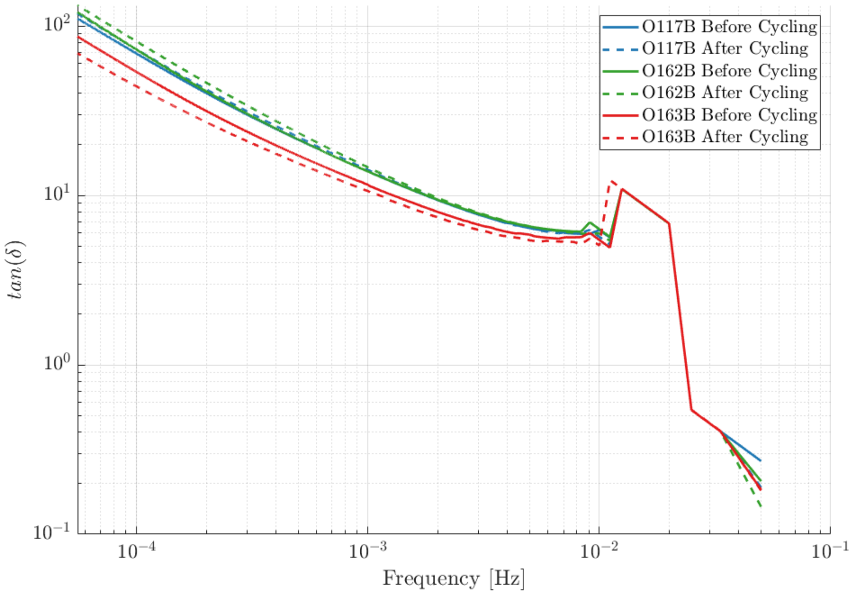


Figure 73: Dielectric loss factor $\tan\delta$ before and after thermal cycling for all bars at 130 °C 10 kV. With the use of polarization current for calculations. O163B has lower losses after cycling while O162B and O117B has higher losses after cycling.

When using depolarization current, the rankings of the bars performance after cycling are the same as with polarization current, as seen in Figure 74 - 76. The most significant difference here is that for all tests above 90 °C, the lowest losses are after cycling. With the small exception of the lowest frequency where results before cycling flattens out a bit more than after cycling. It is still believed that a clear trend is found for the two highest temperatures, while for the two lowest there were no clear trend to spot as there are more noise and variations in the test results. The two lowest temperatures also had the same issue as with polarization results, that it is a bit random whether the current is higher or lower after cycling. The difference in depolarization current before and after cycling is much smaller than polarization current, the dielectric loss factor is therefore much closer in magnitude for the depolarization results.

These observations makes it more difficult to determine trends for the cyclings impact. More deterioration is believed to lead to higher losses, which is not the case with the use of depolarization. The fact that the current difference for depolarization is much lower than for polarization, and that the losses are mostly lower, indicating no increase in deterioration. It is believed the results mostly contribute to the megger being inaccurate for dielectric response on these objects.

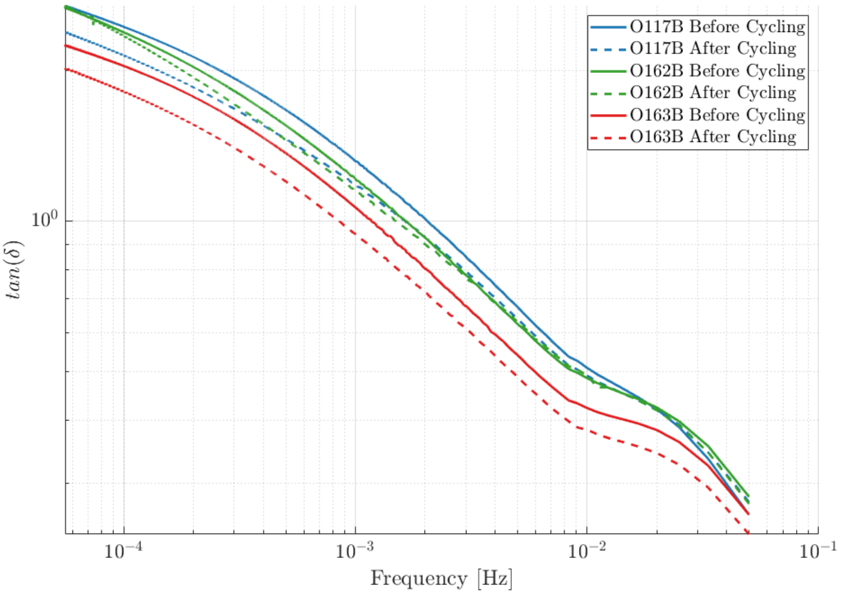


Figure 74: Dielectric loss factor $\tan\delta$ before and after thermal cycling for all bars at 90 °C 5 kV. With the use of depolarization current for calculations. All losses after cycling are lower than before. This is the same as what was observed for the polarization based losses on the same tests.

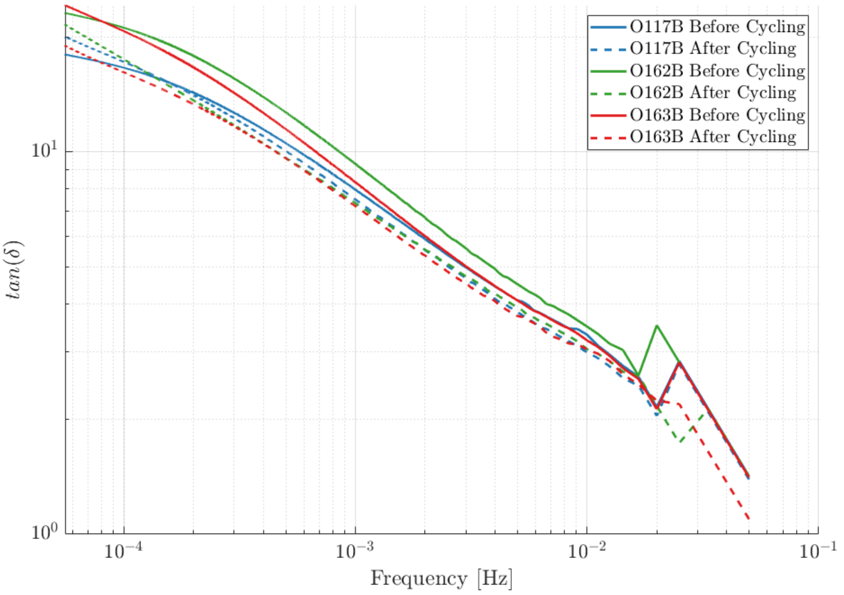


Figure 75: Dielectric loss factor $\tan\delta$ before and after thermal cycling for all bars at 130 °C 2 kV. With the use of depolarization current for calculations. Again all losses are lower after cycling than before. This is now the opposite of the polarization based losses.

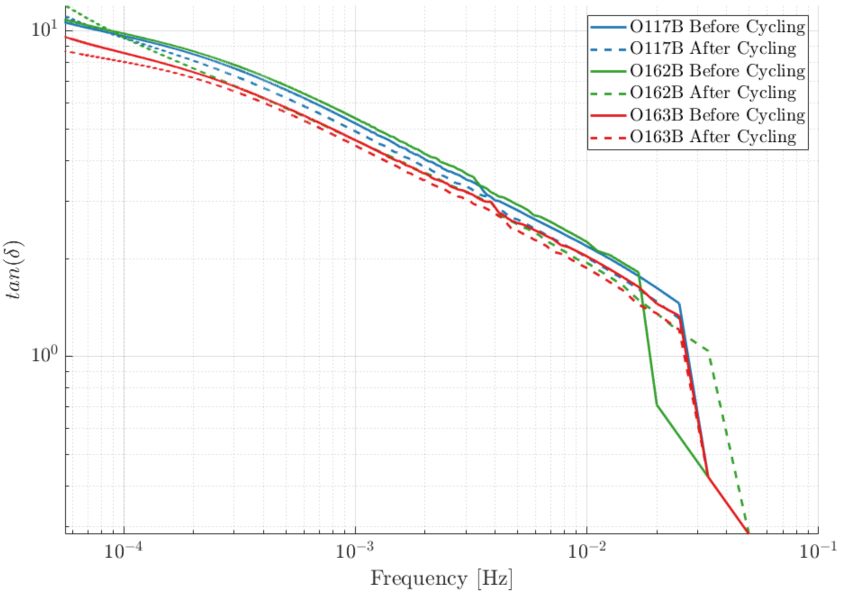


Figure 76: Dielectric loss factor $\tan\delta$ before and after thermal cycling for all bars at 130 °C 10 kV. With the use of depolarization current for calculations.

3.5.4 Conductivity

Figure 77 - 79 shows the comparison of conductivity before and after thermal cycling. The conductivity plots show similarity with the DC plots. As expected, the randomness of whether the measured current are greater or lower after cycling is also shown in the conductivity plots. They coincides yet again with the dielectric losses, the bars with the highest conductivity for a test has the highest losses on the same tests. There is therefore no new information not already discussed in the previous subsection. The randomness of the current increase or decrease after cycling is the key information which comparisons before and after thermal cycling has provided.

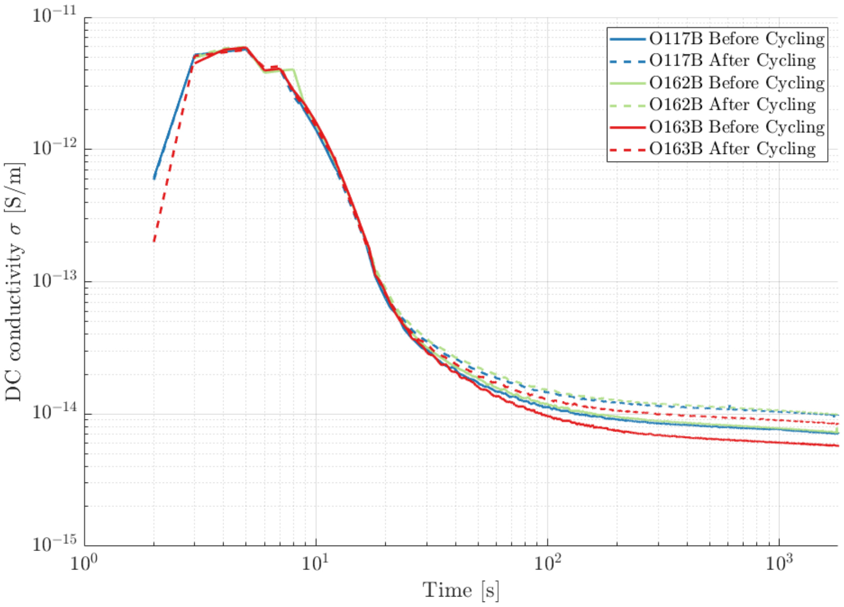


Figure 77: DC conductivity σ as a function of time for all bars before and after Cycling at 60 °C 5 kV. These tests show that all bars had higher conductivity after cycling.

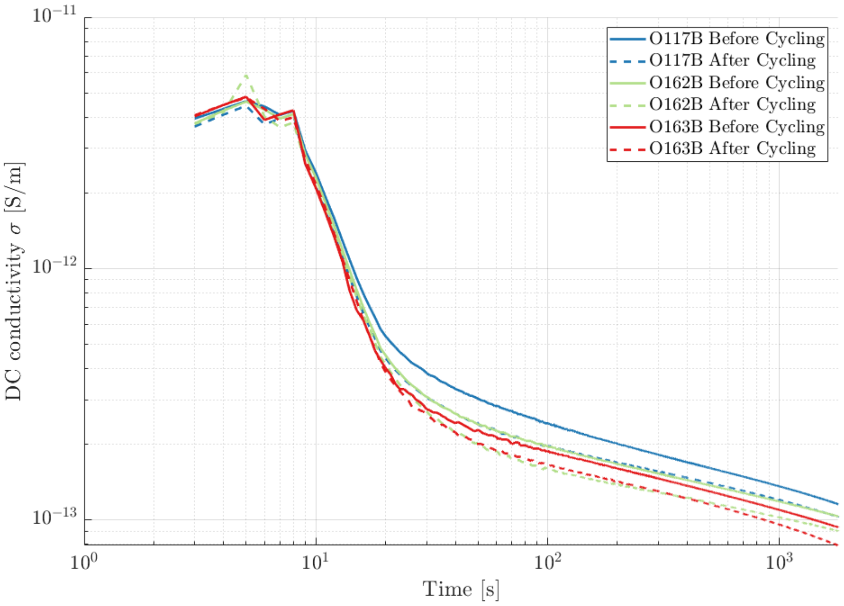


Figure 78: DC conductivity σ as a function of time for all bars before and after Cycling at 90 °C 5kV. These plots show that all the bars now has higher conductivity before cycling.

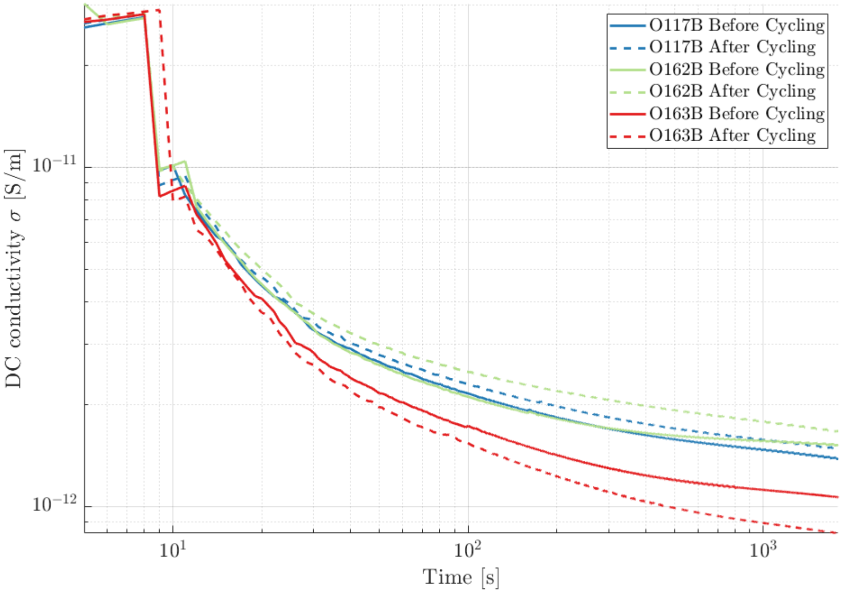


Figure 79: DC conductivity σ as a function of time for all bars before and after Cycling at 130 °C 10 kV. All bars except O163B has higher conductivity after cycling for these tests.

3.6 Feasibility of the megger for dielectric response

The method of dielectric response is a powerful tool for condition assessment, as there is a multitude of variables and factors which can be investigated in order to determine an insulators condition. Dielectric loss factor and the DC conductivity is especially of interests. The only clear downside with the method is that without values to compare with, it is difficult to know which level of deterioration is present in the components. Either the manufacturers or the utilities need to conduct dielectric response before operations of a component or equipment begins. In that way it is possible to compare values which will be recorded during the lifetime of the equipment. The method is therefore best suited for continuous monitoring of several years.

The main strength of a megger is that its portable, easy to use and has a multitude of tests to determine the condition of equipment. Making it a great tool for in field testing. The personnel using the megger does not need to have a deep understanding of the component or equipment's inner workings and only need to save the data for easy comparison. This strength of the megger is not available in the same extent for dielectric response tests. A significant amount of data manipulation is needed, as all the values of interests is not directly measured by the megger, but instead derived through calculations. The Matlab script used in the thesis, all though not the most efficient, is of quite extensive size. Meaning a lot more time and effort is needed for analyzing the condition. It is possible for a utility to provide the testers with the desired equations, for instance dielectric loss, and set a certain time they wish calculations to be performed. In that way it can still be used as simple field test but it will not provide the full picture.

The megger is supposed to make dielectric response as simple as its other test options with the use their own defined DD value. The DD value is supposed to inform the tester of the condition with a simple calculation and comparison of defined table values. The problem with this is that megger has not clearly defined the DD value or the table for comparison. According to the DD value, all bars were both in perfect and in bad condition. Depending only on which voltage and temperature results were used. Without more clear explanation from Megger on how the DD value is to be used, it is difficult to use it for any analysis. Which is why the DD value has not been discussed in the thesis beyond here.

The megger does produce somewhat satisfactory results, which are usable for analysis. It also has its fair share of issues. Low currents are problematic, leading to non credible results as the megger attempts to estimate results instead of measuring them correctly. This was found to be occurring at a measured current of 0.68 nA. This is where the megger measures a maximum resistance of 3 TΩ. When this is the case, all values from the remainder of the test tend to have significant variations, or noise, and also wrongly calculates the current. This is evident with several of the polarization/depolarization current plots and DC plots, where negative DC current was observed. This is caused by a depolarization current being larger in absolute value than the polarization current, which does not make sense according to the discussed literature. It was found that the problem would not occur if it took a long enough time before the maximum resistance were reached. Most likely as this gave the megger more data points to extrapolate from.

The meggers issue with the test setup is not just limited to the lowest currents. Also several cases where the current was above the 1 nA sensitivity level, could strange behavior be observed. In most cases all of these occurred on 2 kV tests. Indicating that not only were it a problem with low currents from low temperature and voltage, but also that the megger has a problem with the 2 kV setting for this type of object. Without another megger to test with, it is impossible to say if this was a equipment specific malfunction or if its a limitation of the megger or even if it was just a coincidence. Several times the megger could not even start its tests properly on 2 kV tests for any temperature, needing several retries.

Throughout testing, it is also evident that the megger has a randomness to its measurements. Bars who for several tests had extremely close measurements results, could suddenly have significantly different results on other tests. It was also observed cases in which a test had a currents which were at the same level as another test on a lower temperature on specific voltage. Before results were again following the trends on the next voltage test. The randomness also became clear after no trend could be observed when comparing results before thermal cycling to those after. Whether a test had higher or lower current after the cycling varied randomly, and there could be quite significant differences in current of up to ± 20 % in the most severe cases.

In general, most plots showed lower variations and more clear trends for all the tests at 90 and 130 °C. These tests had for the most part little noise, and showed the most cases of plots similar to the literature. Although 1 nA measured current was found to be the sensitivity level in which greater noise began there is also noise/ variations at higher current. This may indicate that the megger in fact needs to be above the 20 nA area for credible results. At this current level there is almost no noise and the tests which had this current rarely showed any strange behavior or indications of incorrect measurement. Such as a negative DC current. For these tests, the megger was able to several times plot which bar had the highest and lowest dielectric losses. Although the exact measured current may show some randomness and strange behavior, the higher temperature tests speak well for the method itself, even though the megger has some accuracy issues.

Unfortunately only one test could be performed per voltage and temperature level given time constraints. This means that these findings only lay a foundations for further analysis. The megger might have more issues than able to observe from the tests. It might also be the case that these issues are not problematic enough and that solutions to the problems exists. It is hard to fully determine based on the small test samples that was available. It is also important to note that actual use of this method by utilities will be on completely different components. These components might have much higher capacitance, meaning the problems from smaller currents may not be any factor at all. If the bars tested were twice the length, there would be twice the capacitance and twice the current. An actual hydropower generator will often have over a hundred bars in parallel that is tested on at the same time. For single bars, the megger only produce credible results on the two highest temperature levels as this is where the results have the leas amount of noise and tends to show more clear trends in the objects performance. At the same time, the megger also experienced some issues or strange behavior on these higher temperatures as well.

4 Conclusion

The condition assessment method of dielectric response has been conducted with the use of a megger, on service aged hydropower generator stator bars. The sensitivity level for the megger was found to be currents of 1 nA. Measurements below this showed trends of inaccuracies and noise of up to ± 20-30 % current variation per second. Noise was also visible for currents below 20 nA, though not as severe. Tests whose results were lower than 1 nA had several cases of incorrect measurements, i.e polarization current being lower than depolarization current which goes against the theory. The megger were found to have a maximum resistance of 3 TΩ occurring only for 20 °C 2 kV tests at a measured current of 0.68 nA. These results had the same issues as those measured at 1 nA, only more severe.

On 90 and 130 °C test, the currents are above 20 nA, producing no visible or significant noise and clear trends of the bars behavior were observed. These results showed a clear correlation between the bars current, DC conductivity and dielectric loss. Some higher current results on these temperatures were also found to show inaccuracy and sometimes test anomalies. i.e the measured current were on the level of a much lower temperature test. The meggers measurement issues, regardless of temperature and voltage, were found to be mostly caused by the calculated insulation resistance. Since they were only occurring for the polarization part of the tests.

The test method was able to find the dielectric losses of the bars, and which bar had the lowest or highest losses remained the same for tests of 90 °C and above. Linearity was found in the bars, showing that the losses and conductivity was almost solely dependent on the temperature. Some voltage dependency was found and is believed to be caused by the increased current, and thus increased accuracy.

Thermal cycling of 220 cycles following IEEE std 1310 were found to have no significant impact on the bars condition. Whether the current was higher or lower after cycling was found to be random, with the plots being closely identical in shape. Which bar had the lowest or highest losses and conductivity remained mostly the same, with some difference depending on whether the current was higher or lower after cycling.

When validating the megger for dielectric response, the method itself has been found to have great potential for condition assessment. For it to be of any use, data from unaged bars are needed for comparisons. The variables of interest, DC conductivity and dielectric loss, can not be extracted directly from the megger. Meaning significant amount of data manipulation is needed for analysis. This negates the benefit of the meggers ease of use and as a simple in the field testing equipment. The megger does not function satisfactory as equipment for the method on single bars as objects because of the observed random measurement behavior and inaccuracies with low currents. This may not be a issue for utilities as they will be testing on larger components with higher capacitance. More testing on such objects with higher capacitance or lower resistance, which leads to higher currents, are needed in order to fully determine if a megger is a good equipment choice for dielectric response.

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Appendix

A Matlab script

First matlab script analyzing all tests before thermal cycling

```
close all; clear all;clc;
scrsz = get(0,'ScreenSize'); %Get the screen size to set the figure appropriate
addpath('Functions')
set(groot,'defaultAxesTickLabelInterpreter','latex');
set(groot,'defaulttextinterpreter','latex');
set(groot,'defaultLegendInterpreter','latex');

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%% Chose parameters: %%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

saveON = 0;
prpdaON = 0;
figureWidth = 6; %cm for font scaling
figureWidthPRPDA = 8; %cm
fontsize = 8*20/figureWidthPRPDA;

linewidth = 3;

pathX = 'C:\Users\danie\Desktop\MasterMatlab';

bars = {'O117B','O120B','O162B','O163B',};


temperatures = [20 60 90 130];
voltages = [2 5 10];
C = 2.840 * 1e-9; %Measured capacitance of objects%
eR = 4.455; %calculated relative permittivity
e0 = 8.854 *1e-12;

Data = zeros(length(bars),length(temperatures),length(voltages),3591,3);
I_DC = zeros(length(bars),length(temperatures),length(voltages));
tanD = zeros(length(bars),length(temperatures),length(voltages),3591); %For pol
```

```
tanD2 = zeros(length(bars),length(temperatures),length(voltages),3591); %For depol

for i = 1:length(bars)
    for j = 1:length(temperatures)
        for k = 1:length(voltages)
            mpath = sprintf('%s\\Test1_%s_%dC_%dkV.txt',pathX,bars{i},temperatures(j),voltages(k));
            A{i}{j}{k} = readmatrix(mpath,'Range','J:M');

            T = readtable(mpath);
            timeDataX = T(:,9);
            timeDataY{i}{j}{k} = table2array(timeDataX);
            timeData = char(timeDataY{i}{j}{k}); % NB Matlab2020


            for m = 1:size(timeData,1)
                seconds{i}{j}{k}(m) = str2double(timeData(m,1:2)).*60*60+str2double(timeData(m,4:5)).*60+str2double(timeData(m,7:8));
            end

            tmp(:,:) = A{i}{j}{k}(:,1:3);
            Data(i,j,k,1:size(tmp,1),1:3) = tmp;

            tmp2(:) = tmp(:,2);
            tmpPol = tmp2(tmp(:,1)>100);
            tmpDepol = tmp2(tmp(:,1)<100);
            len1 = length(tmpPol);
            len2 = length(tmpDepol);
            len = min(len1, len2);
            tmp3(:) = tmpPol(1:len) - tmpDepol(1:len);


            I_DC(i,j,k) = mean(tmp3(end/2+1:end));%mikroA %
            tmpSeconds(:) = seconds{i}{j}{k};
            tanD(i,j,k,1:length(tmpPol)) = (tmpPol .*1e-6 .*tmpSeconds(1:length(tmpPol)))/(0.63 .* C .*voltages(k) .*1000); %*1000 for Volts
            tanD2(i,j,k,1:length(tmpDepol)) = (tmpDepol .*1e-6 .*tmpSeconds(1:length(tmpDepol)))/(0.63 .* C .*voltages(k) .*1000);
```

```
            Sigma{i}{j}{k} = (e0 .* eR .*I_DC(i,j,k) .* 1e-6)/(voltages(k) .*1000 .* C);
            Sigmat{i}{j}{k}(:) = (e0 .* eR .* tmp3.* 1e-6)/(voltages(k) .*1000 .* C); %For time dependence sigma
            clear tmp tmp2 tmp3
        end
    end
end

%Plotting



colors = [   166,206,227
             31,120,180
             178,223,138
             51,160,44
             251,154,153
             227,26,28
             253,191,111
             255,127,0
             202,178,214
             106,61,154
             255,255,153
             177,89,40
             ]/255;


%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%% Plot the data: %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

markers1 = {'ok' 'sk' 'dk' '^k' 'vk' '<k'};
markers2 = {':ok' ':sk' ':dk' ':^k' ':vk' ':<k'};
markers3 = {'--ok' '--^k' '--dk' '--hk' '--vk' '--<k'};
markers4 = {'-o' '-^' '-d' '-h' '-v' '-<' '--^' '--d' '--h' '--v' '--<'};
markers5 = {'-' '--' ':' '-.' '-o'};

facecolor = [0,1];


```

```
%%%
%Plots pol and depol current for the different bars for one temp and one
%voltage

% for i = 1:length(bars)
%     for j = 1:length(temperatures)
%         for k = 1: length(voltages)
%
%             figure1 = figure('Position',[20 20 1.5*scrsz(4)*2/3 scrsz(4)*2/3],'PaperSize',[1.5*16 16],'PaperPositionMode', 'auto');
%             hold on
%             tmp2(:) = Data(i,j,k,:,2)*1000; %Endre hvilke data som plottes Data(i,j,k,:,2)
%             tmp3(:) = tmp2(1:end/2)-tmp2(end/2+1:end); %
%             tmpSeconds(:) = seconds{i}{j}{k}(:);
%
%             plot(tmpSeconds(1:end/2),tmp2(1:end/2),markers5{1},'LineWidth',2,'Color',colors(1,:),'Markersize',10)
%             plot(tmpSeconds(1:end/2),tmp2(end/2+1:end),markers5{2},'LineWidth',2,'Color',colors(2,:),'Markersize',10)
%             ylabel('$I_{POL/DEPOL}$ (nA)')
%             xlabel('Time [s]')
%
%             set(gca,'YMinorTick','on','YScale','log')%,'YTick',[0.1 1 10 100 1000]);
%             set(gca,'XMinorTick','on','XScale','log')%,'XTick',[0.1 1 10 100 1000],'XTickLabel',{' ',' ',' ',' ',' '});
%             set(gca,'FontSize',5*20/figureWidth);
%             Tittel = sprintf ('%s %d %s%s %d %s', bars{i}, temperatures(j), 'C',char(176) , voltages(k), 'kV');
%             title(Tittel)
%             legend('Polarization','Depolarization','Location','NorthEast');
%             legend('boxoff')
%             grid on
%
%             %Fignavn = sprintf('%s_%d%s_%d_%s', bars{i}, temperatures(j),'C', voltages(k), 'kV');
%             %bane = 'C:\Users\danie\Desktop\Plots\Pol_Depol';
%             %saveas(figure1,sprintf('%s\%s.png', bane, Fignavn))
```

```
%         end
%     end
% end
%%

%%
%Plots several bars pol


%     for j = 1:length(temperatures)
%         for k = 1: length(voltages)
%
%             figure1 = figure('Position',[20 20 1.5*scrsz(4)*2/3 scrsz(4)*2/3],'PaperSize',[1.5*16 16],'PaperPositionMode', 'auto');
%             hold on
%             tmp2(:) = Data(1,j,k,:,2)*1000; %Endre hvilke data som plottes Data(i,j,k,:,2)
%             tmp3(:) = Data(2,j,k,:,2)*1000;
%             tmp4(:) = Data(3,j,k,:,2)*1000;
%             tmp5(:) = Data(4,j,k,:,2)*1000;
%             tmpSeconds(:) = seconds{i}{j}{k}(:);
%
%             plot(tmpSeconds(1:end/2),tmp2(1:end/2),markers5{1},'LineWidth',2,'Color',colors(1,:),'Markersize',10)
%             plot(tmpSeconds(1:end/2),tmp3(1:end/2),markers5{1},'LineWidth',2,'Color',colors(2,:),'Markersize',10)
%             plot(tmpSeconds(1:end/2),tmp4(1:end/2),markers5{1},'LineWidth',2,'Color',colors(4,:),'Markersize',10)
%             plot(tmpSeconds(1:end/2),tmp5(1:end/2),markers5{1},'LineWidth',2,'Color',colors(5,:),'Markersize',10)
%             ylabel('$I_{POL}$ (nA)')
%             xlabel('Time [s]')
%
%             set(gca,'YMinorTick','on','YScale','log')%,'YTick',[0.1 1 10 100 1000]);
%             set(gca,'XMinorTick','on','XScale','log')%,'XTick',[0.1 1 10 100 1000],'XTickLabel',{' ',' ',' ',' ',' '});
%             set(gca,'FontSize',5*20/figureWidth);
%             Tittel = sprintf ('%s %d %s%s %d %s', 'Polarization current', temperatures(j), 'C',char(176) , voltages(k), 'kV');
%             title(Tittel)
```

```
%             legend('O117B','O120B','O162B','O163B','Location','NorthEast');
%             legend('boxoff')
%             grid on
%
%
%         end
%     end
%%%

%%%
%Plots DC current as function of time

% for i = 1:length(bars)
%     for j = 1:length(temperatures)
%         for k = 1:length(voltages)
%
%             figure2 = figure('Position',[20 20 1.5*scrsz(4)*2/3 scrsz(4)*2/3],'PaperSize',[1.5*16 16],'PaperPositionMode', 'auto');
%             hold on
%             tmp2(:) = Data(i,j,k,:,2)*1000;
%
%             % %tmpTP(:) = Data(2,j,k,:,2)*1000; For sammenligning
%
%             tmpSeconds(:) = seconds{i}{j}{k}(:);
%             plot(tmpSeconds(1:end/2),tmp2(1:end/2)-tmp2(end/2+1:end),markers5{1},'LineWidth',2,'Color',colors(1,:),'Markersize',10)
%
%             % %plot(tmpSeconds(1:end/2),tmpTP(1:end/2)-tmpTP(end/2+1:end),markers5{2},'LineWidth',2,'Color',colors(2,:),'Markersize',10)(for
%             % sammenligning)
%
%             ylabel('$I_{DC}$ [nA]')
%             xlabel('Time [s]')
%             Tittel = sprintf ('%s %d %s%s %d %s', bars{i}, temperatures(j), 'C',char(176) , voltages(k), 'kV');
%             title(Tittel)
%             %(Add Legend)
%             grid on
```

```
%               set(gca,'YMinorTick','on','YScale','log')%,'YTick',[0.1 1 10 100 1000]);
%               set(gca,'XMinorTick','on','XScale','log')%,'XTick',[0.1 1 10 100 1000],'XTickLabel',{' ',' ',' ',' ',' '});
%               set(gca,'FontSize',5*20/figureWidth);
%
%           end
%       end
% end
%%%

%%%
%Plots DC current for all bars in the same plot

%       for j = 1:length(temperatures)
%           for k = 1:length(voltages)
%
%               figure2 = figure('Position',[20 20 1.5*scrsz(4)*2/3 scrsz(4)*2/3],'PaperSize',[1.5*16 16],'PaperPositionMode', 'auto');
%               hold on
%               tmp2(:) = Data(1,j,k,:,2)*1000;
%               tmp3(:) = Data(2,j,k,:,2)*1000;
%               tmp4(:) = Data(3,j,k,:,2)*1000;
%               tmp5(:) = Data(4,j,k,:,2)*1000;
%
%
%
%               tmpSeconds(:) = seconds{i}{j}{k}(:);
%               plot(tmpSeconds(1:end/2),tmp2(1:end/2)-tmp2(end/2+1:end),markers5{1},'LineWidth',2,'Color',colors(1,:),'Markersize',10)
%               plot(tmpSeconds(1:end/2),tmp3(1:end/2)-tmp3(end/2+1:end),markers5{1},'LineWidth',2,'Color',colors(2,:),'Markersize',10)
%               plot(tmpSeconds(1:end/2),tmp4(1:end/2)-tmp4(end/2+1:end),markers5{1},'LineWidth',2,'Color',colors(4,:),'Markersize',10)
%               plot(tmpSeconds(1:end/2),tmp5(1:end/2)-tmp5(end/2+1:end),markers5{1},'LineWidth',2,'Color',colors(5,:),'Markersize',10)
%
%               ylabel('$I_{DC}$ [nA]')
```

```
%               xlabel('Time [s]')
%               Tittel = sprintf ('%s %d %s%s %d %s','DC current', temperatures(j), 'C',char(176) , voltages(k), 'kV');
%               title(Tittel)
%               grid on
%               set(gca,'YMinorTick','on','YScale','log')%,'YTick',[0.1 1 10 100 1000]);
%               set(gca,'XMinorTick','on','XScale','log')%,'XTick',[0.1 1 10 100 1000],'XTickLabel',{' ',' ',' ',' ',' '});
%               set(gca,'FontSize',5*20/figureWidth);
%               legend('O117B','O120B','O162B','O163B','Location','NorthEast');
%               legend('boxoff')
%
%           end
%       end
%%

%%
%Plots DC current as function of temperature

% figure3 = figure('Position',[20 20 1.5*scrsz(4)*2/3 scrsz(4)*2/3],'PaperSize',[1.5*16 16],'PaperPositionMode', 'auto');
% hold on
% tmp4(:) = I_DC(1,:,1)*1000;
% plot(temperatures,tmp4,markers4{1},'LineWidth',2,'Color',colors(1,:),'Markersize',10)
% ylabel('$I_{DC}$ [nA]')
% xlabel('Temperature ($^oC$)')
% set(gca,'YMinorTick','on','YScale','lin')%,'YTick',[0.1 1 10 100 1000]);
% set(gca,'XMinorTick','on','XScale','lin')%,'XTick',[0.1 1 10 100 1000],'XTickLabel',{' ',' ',' ',' ',' '});
% set(gca,'FontSize',5*20/figureWidth);
%%

%%
%Plots DC current as fucntion of voltage

% figure4 = figure('Position',[20 20 1.5*scrsz(4)*2/3 scrsz(4)*2/3],'PaperSize',[1.5*16 16],'PaperPositionMode', 'auto');
% hold on
% tmp5(:) = I_DC(1,1,:)*1000;
```

```
% plot(voltages,tmp5,markers4{1},'LineWidth',2,'Color',colors(1,:),'Markersize',10)
% ylabel('$I_{DC}$ [nA]')
% xlabel('Voltage (kV)')
% set(gca,'YMinorTick','on','YScale','lin')%,'YTick',[0.1 1 10 100 1000]);
% set(gca,'XMinorTick','on','XScale','lin')%,'XTick',[0.1 1 10 100 1000],'XTickLabel',{' ',' ',' ',' ',' '});
% set(gca,'FontSize',5*20/figureWidth);
%%

%%
%Plots TanDelta as function of temperature
%same plot)

% figure5 = figure('Position',[20 20 1.5*scrsz(4)*2/3 scrsz(4)*2/3],'PaperSize',[1.5*16 16],'PaperPositionMode', 'auto');
% hold on
% % % % tmp6X(:,:) = tanD(1,:,1,1000:1020);
% % % % tmp6(:) = mean(tmp6X,2);
% tmp6(:) = tanD(1,:,1, 100); %M  velge ut noen tidspunkter av interesse
% plot(temperatures,tmp6,markers4{1},'LineWidth',2,'Color',colors(1,:),'Markersize',10)
% ylabel('tan($\delta$)')
% xlabel('Temperature ($^oC$)')
% set(gca,'YMinorTick','on','YScale','log')%,'YTick',[0.1 1 10 100 1000]);
% set(gca,'XMinorTick','on','XScale','lin')%,'XTick',[0.1 1 10 100 1000],'XTickLabel',{' ',' ',' ',' ',' '});
% set(gca,'FontSize',5*20/figureWidth);
%%

%%
%Plots tanDelta (Pol) as function of temperature for several voltages

% for i = 1:length(bars)
% figure5 = figure('Position',[20 20 1.5*scrsz(4)*2/3 scrsz(4)*2/3],'PaperSize',[1.5*16 16],'PaperPositionMode', 'auto');
% hold on
%     for k=1:length(voltages)
%
```

```
%           for j=1:length(temperatures)
%               tmp6(j) = tanD(i,j,k, 600); %M  velge ut noen tidspunkter av interesse
%           end
%           %%% tmp6X(:,:) = tanD(1,:,1,1000:1020);
%           %%% tmp6(:) = mean(tmp6X,2);
%
%           plot(temperatures,tmp6,markers4{k},'LineWidth',2,'Color',colors(k,:),'Markersize',10)
%           ylabel('tan($\delta$)')
%           xlabel('Temperature ($^oC$)')
%           set(gca,'YMinorTick','on','YScale','log')%,'YTick',[0.1 1 10 100 1000]);
%           set(gca,'XMinorTick','on','XScale','lin')%,'XTick',[0.1 1 10 100 1000],'XTickLabel',{' ',' ',' ',' ',' '});
%           set(gca,'FontSize',5*20/figureWidth);
%
%       end
%       grid on
%       legend('2kV','5kV','10kV','Location', 'SouthEast')
%       Tittel = sprintf('%s',bars{i});
%       title(Tittel)
% end

%%%

%%%
%Plots TanDelta, Pol current, as function of voltage for several temperatures

% for i = 1:length(bars)
% figure5 = figure('Position',[20 20 1.5*scrsz(4)*2/3 scrsz(4)*2/3],'PaperSize',[1.5*16 16],'PaperPositionMode', 'auto');
% hold on
%       for j=1:length(temperatures)
%
%           for k=1:length(voltages)
%               tmp6(k) = tanD(i,j,k, 600); %M  velge ut noen tidspunkter av interesse
%           end
%
%
```

```
%           plot(voltages,tmp6,markers4{j},'LineWidth',2,'Color',colors(j,:),'Markersize',10)
%           ylabel('tan($\delta$)')
%           xlabel('Voltage [kV]')
%           set(gca,'YMinorTick','on','YScale','log')%,'YTick',[0.1 1 10 100 1000]);
%           set(gca,'XMinorTick','on','XScale','lin')%,'XTick',[0.1 1 10 100 1000],'XTickLabel',{' ',' ',' ',' ',' '});
%           set(gca,'FontSize',5*20/figureWidth);
%
%       end
%       grid on
%       legend('20 ($^oC$)','60 ($^oC$)','90 ($^oC$)', '130 ($^oC$)','Location','SouthEast')
%       Tittel = sprintf('%s',bars{i});
%       title(Tittel)
% end
%%

%%
%Plots TanDelta, Depol current, as function of voltage for several temperatures

% for i = 1:length(bars)
% figure5 = figure('Position',[20 20 1.5*scrsz(4)*2/3 scrsz(4)*2/3],'PaperSize',[1.5*16 16],'PaperPositionMode', 'auto');
% hold on
%       for j=1:length(temperatures)
%
%           for k=1:length(voltages)
%               tmp6(k) = tanD2(i,j,k, 600); %M  velge ut noen tidspunkter av interesse
%           end
%           % % % tmp6X(:,:) = tanD(1,:,1,1000:1020);
%           % % % tmp6(:) = mean(tmp6X,2);
%
%           plot(voltages,tmp6,markers4{j},'LineWidth',2,'Color',colors(j,:),'Markersize',10)
%           ylabel('tan($\delta$)')
%           xlabel('Voltages [kV]')
%           set(gca,'YMinorTick','on','YScale','log')%,'YTick',[0.1 1 10 100 1000]);
```

```
%         set(gca,'XMinorTick','on','XScale','log')%,'XTick',[0.1 1 10 100 1000],'XTickLabel',{' ',' ',' ',' ',' '});
%         set(gca,'FontSize',5*20/figureWidth);
%
%     end
%     grid on
%     legend('20 ($^oC$)','60 ($^oC$)','90 ($^oC$)', '130 ($^oC$)','Location','SouthEast')
%     Tittel = sprintf('%s',bars{i});
%     title(Tittel)
% end

%%

%%
%Plots TanDelta, Pol current, as function of frequency/time

% for i = 1:length(bars)
%     for j = 1:length(temperatures)
%         for k = 1:length(voltages)
%
%             figure6 = figure('Position',[20 20 1.5*scrsz(4)*2/3 scrsz(4)*2/3],'PaperSize',[1.5*16 16],'PaperPositionMode', 'auto');
%             hold on
%             tmp7(:) = tanD(i,j,k,:);
%             tmpSeconds(:) = seconds{i}{j}{k}(:);
%
%             plot(0.1./tmpSeconds(1:length(tmpPol)),tmp7(1:length(tmpPol)),markers4{1},'LineWidth',2,'Color',colors(1,:),'Markersize',10)
%             ylabel('$tan(\delta)$')
%             xlabel('Frequency [Hz]')
%             Tittel = sprintf ('%s %d %s%s %d %s', bars{i}, temperatures(j), 'C',char(176) , voltages(k), 'kV');
%             title(Tittel)
%             grid on
%             set(gca,'YMinorTick','on','YScale','log')%,'YTick',[0.1 1 10 100 1000]);
%             set(gca,'XMinorTick','on','XScale','log')%,'XTick',[0.1 1 10 100 1000],'XTickLabel',{' ',' ',' ',' ',' '});
%             set(gca,'FontSize',5*20/figureWidth);
%
```

```
%         end
%     end
% end
%%%

%%%
%Plots several tan delta (Pol) as function of frequency/time


%     for j = 1:length(temperatures)
%         for k = 1:length(voltages)
%
%             figure6 = figure('Position',[20 20 1.5*scrsz(4)*2/3 scrsz(4)*2/3],'PaperSize',[1.5*16 16],'PaperPositionMode', 'auto');
%             hold on
%             tmp7(:) = tanD(1,j,k,:);
%             tmp8(:) = tanD(2,j,k,:);
%             tmp9(:) = tanD(3,j,k,:);
%             tmp10(:) = tanD(4,j,k,:);
%             tmpSeconds(:) = seconds{i}{j}{k}(:);
%
%             plot(0.1./tmpSeconds(1:length(tmpPol)),tmp7(1:length(tmpPol)),markers5{1},'LineWidth',2,'Color',colors(1,:),'Markersize',10)
%             plot(0.1./tmpSeconds(1:length(tmpPol)),tmp8(1:length(tmpPol)),markers5{1},'LineWidth',2,'Color',colors(2,:),'Markersize',10)
%             plot(0.1./tmpSeconds(1:length(tmpPol)),tmp9(1:length(tmpPol)),markers5{1},'LineWidth',2,'Color',colors(3,:),'Markersize',10)
%             plot(0.1./tmpSeconds(1:length(tmpPol)),tmp10(1:length(tmpPol)),markers5{1},'LineWidth',2,'Color',colors(5,:),'Markersize',10)
%             ylabel('$tan(\delta)$')
%             xlabel('Frequency [Hz]')
%             Tittel = sprintf ('%d %s%s %d %s', temperatures(j), 'C',char(176) , voltages(k), 'kV');
%             title(Tittel)
%             grid on
%             legend('O117B','O120B','O162B','O163B','Location','NorthEast')
```

```
%             set(gca,'YMinorTick','on','YScale','log')%,'YTick',[0.1 1 10 100 1000]);
%             set(gca,'XMinorTick','on','XScale','log')%,'XTick',[0.1 1 10 100 1000],'XTickLabel',{' ',' ',' ',' ',' '});
%             set(gca,'FontSize',5*20/figureWidth);
%
%         end
%     end

%%

%%
%Plots several tan delta (Depol Current) as function of frequency/time


%     for j = 1:length(temperatures)
%         for k = 1:length(voltages)
%
%             figure6 = figure('Position',[20 20 1.5*scrsz(4)*2/3 scrsz(4)*2/3],'PaperSize',[1.5*16 16],'PaperPositionMode', 'auto');
%             hold on
%             tmp7(:) = tanD2(1,j,k,:);
%             tmp8(:) = tanD2(2,j,k,:);
%             tmp9(:) = tanD2(3,j,k,:);
%             tmp10(:) = tanD2(4,j,k,:);
%             tmpSeconds(:) = seconds{i}{j}{k}(:);
%
%             plot(0.1./tmpSeconds(1:length(tmpDepol)),tmp7(1:length(tmpDepol)),markers5{1},'LineWidth',2,'Color',colors(1,:),'Markersize',10)
%             plot(0.1./tmpSeconds(1:length(tmpDepol)),tmp8(1:length(tmpDepol)),markers5{1},'LineWidth',2,'Color',colors(2,:),'Markersize',10)
%             plot(0.1./tmpSeconds(1:length(tmpDepol)),tmp9(1:length(tmpDepol)),markers5{1},'LineWidth',2,'Color',colors(3,:),'Markersize',10)
%             plot(0.1./tmpSeconds(1:length(tmpDepol)),tmp10(1:length(tmpDepol)),markers5{1},'LineWidth',2,'Color',colors(5,:),'Markersize',10)
%             ylabel('$tan(\delta)$')
%             xlabel('Frequency [Hz]')
```

```
%             Tittel = sprintf ('%d %s%s %d %s', temperatures(j), 'C',char(176) , voltages(k), 'kV');
%             title(Tittel)
%             grid on
%             legend('O117B','O120B','O162B','O163B','Location','NorthEast')
%             set(gca,'YMinorTick','on','YScale','log')%,'YTick',[0.1 1 10 100 1000]);
%             set(gca,'XMinorTick','on','XScale','log')%,'XTick',[0.1 1 10 100 1000],'XTickLabel',{' ',' ',' ',' ',' '});
%             set(gca,'FontSize',5*20/figureWidth);
%
%         end
%     end

%%

%%
%Plots Sigma as function of temperature

% for i = 1:length(bars)
%
%     figure7 = figure('Position',[20 20 1.5*scrsz(4)*2/3 scrsz(4)*2/3],'PaperSize',[1.5*16 16],'PaperPositionMode', 'auto');
%     hold on
%     for k = 1:length(voltages)
%
%         for j = 1:length(temperatures)
%             tmp8(j) = Sigma{i}{j}{k};
%
%         end
%
%         plot(temperatures,tmp8,markers4{k},'LineWidth',2,'Color',colors(k,:),'Markersize',10)
%
%         ylabel('DC conductivity $\sigma$ [S/m]','interpreter','latex')
%         xlabel('Temperature ($^oC$)')
%         set(gca,'YMinorTick','on','YScale','log')%,'YTick',[0.1 1 10 100 1000]);
%         set(gca,'XMinorTick','on','XScale','lin')%,'XTick',[0.1 1 10 100 1000],'XTickLabel',{' ',' ',' ',' ',' '});
%         set(gca,'FontSize',5*20/figureWidth);
```

```
%
%     end
%     grid on
%     legend('2 kV','5 kV','10 kV','Location','SouthEast')
%     Tittel = sprintf('%s',bars{i});
%     title(Tittel)
%
% end

%%

%%
%Plots Sigma as function of voltages

% for i = 1:length(bars)
%     figure8 = figure('Position',[20 20 1.5*scrsz(4)*2/3 scrsz(4)*2/3],'PaperSize',[1.5*16 16],'PaperPositionMode', 'auto');
%     hold on
%
%     for j = 1:length(temperatures)
%
%         for k = 1:length(voltages)
%             tmp9(k) = Sigma{i}{j}{k};
%         end
%
%
%         plot(voltages,tmp9,markers4{j},'LineWidth',2,'Color',colors(j,:),'Markersize',10)
%         ylabel('DC conductivity $\sigma$ [S/m]','interpreter','latex')
%         xlabel('Voltages [kV]')
%         set(gca,'YMinorTick','on','YScale','log')%,'YTick',[0.1 1 10 100 1000]);
%         set(gca,'XMinorTick','on','XScale','lin')%,'XTick',[0.1 1 10 100 1000],'XTickLabel',{' ',' ',' ',' ',' '});
%         set(gca,'FontSize',5*20/figureWidth);
%
%
%     end
%     grid on
%     legend('20 ($^oC$)','60 ($^oC$)','90 ($^oC$)', '130 ($^oC$)','Location','SouthEast')
%     Tittel = sprintf('%s',bars{i});
```

```
%     title(Tittel)
% end
%%

%%
%Plots Sigma as a function of time

% len1 = length(tmpPol);
% len2 = length(tmpDepol);
% len = min(len1, len2);
%
% for i = 1:length(bars)
%     for j = 1:length(temperatures)
%         for k = 1:length(voltages)
%
%             figure6 = figure('Position',[20 20 1.5*scrsz(4)*2/3 scrsz(4)*2/3],'PaperSize',[1.5*16 16],'PaperPositionMode', 'auto');
%             hold on
%             tmp7(:) = Sigmat{i}{j}{k}(:);
%
%             tmpSeconds(:) = seconds{i}{j}{k}(:);
%
%             plot(tmpSeconds(1:len),tmp7(1:len),markers5{1},'LineWidth',2,'Color',colors(2,:),'Markersize',10)
%
%             ylabel('DC conductivity $\sigma$ [S/m]','interpreter','latex')
%             xlabel('Time [s]')
%             Tittel = sprintf ('%s %d %s%s %d %s', bars{i}, temperatures(j), 'C',char(176) , voltages(k), 'kV');
%             title(Tittel)
%             grid on
%             set(gca,'YMinorTick','on','YScale','log')%,'YTick',[0.1 1 10 100 1000]);
%             set(gca,'XMinorTick','on','XScale','log')%,'XTick',[0.1 1 10 100 1000],'XTickLabel',{' ',' ',' ',' ',' '});
%             set(gca,'FontSize',5*20/figureWidth);
%
%         end
%     end
% end
%%
```

```

%Plots Sigma for all bars as a function of time

% len1 = length(tmpPol);
% len2 = length(tmpDepol);
% len = min(len1, len2);
%
% %for i = 1:length(bars)
%     for j = 1:length(temperatures)
%         for k = 1:length(voltages)
%
%             figure6 = figure('Position',[20 20 1.5*scrsz(4)*2/3
  scrsz(4)*2/3],'PaperSize',[1.5*16 16],'PaperPositionMode', '
 auto');
%             hold on
%             tmp7(:) = Sigmat{1}{j}{k}(:);
%
%             tmp8(:) = Sigmat{2}{j}{k}(:);
%             tmp9(:) = Sigmat{3}{j}{k}(:);
%             tmp10(:) = Sigmat{4}{j}{k}(:);
%             tmpSeconds(:) = seconds{i}{j}{k}(:);
%
%             plot(tmpSeconds(1:len),tmp7(1:len),markers5{1},'
 LineWidth',2,'Color',colors(2,:),'Markersize',10)
%
%             plot(tmpSeconds(1:len),tmp8(1:len),markers5{1},'
 LineWidth',2,'Color',colors(3,:),'Markersize',10)
%             plot(tmpSeconds(1:len),tmp9(1:len),markers5{1},'
 LineWidth',2,'Color',colors(6,:),'Markersize',10)
%             plot(tmpSeconds(1:len),tmp10(1:len),markers5{1},'
 LineWidth',2,'Color',colors(8,:),'Markersize',10)
%             ylabel('DC conductivity $\sigma$ [S/m]','
 interpreter','latex')
%             xlabel('Time [s]')
%             Tittel = sprintf ('%d %s%s %d %s', temperatures(j),
  'C',char(176) , voltages(k), 'kV');
%             title(Tittel)
%             grid on
%             legend('O117B', 'O120B', 'O162B', 'O163B' ,'
 Location', 'Northeast')
%             set(gca,'YMinorTick','on','YScale','log')%,'YTick
 ',[0.1 1 10 100 1000]);
```

```
%                 set(gca,'XMinorTick','on','XScale','log')%,'XTick',[0.1 1 10 100 1000],'XTickLabel',{' ',' ',' ',' ',' '});
%                 set(gca,'FontSize',5*20/figureWidth);
%
%             end
%         end
%end
%%%
```

Second matlab script adapted from the first to compare results before and after thermal cycling

```
close all; clear all;clc;
scrsz = get(0,'ScreenSize'); %Get the screen size to set the figure appropriate
addpath('Functions')
set(groot,'defaultAxesTickLabelInterpreter','latex');
set(groot,'defaulttextinterpreter','latex');
set(groot,'defaultLegendInterpreter','latex');

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%% Chose parameters: %%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

saveON = 0;
prpdaON = 0;
figureWidth = 6; %cm for font scaling
figureWidthPRPDA = 8; %cm
fontsize = 8*20/figureWidthPRPDA;

linewidth = 3;

pathX = 'C:\Users\danie\Desktop\MasterMatlab';


%bars = {'O117B','O120B','O162B','O163B',};%

bars = {'O117B','O117B2','O162B','O162B2','O163B','O163B2'}; % For comparison before and after cycling

temperatures = [20 60 90 130];
voltages = [2 5 10];
C = 2.840 * 1e-9;%Capacitance of objects%
```

```
eR = 4.455; %Calculated permittivity
e0 = 8.854 *1e-12;

Data = zeros(length(bars),length(temperatures),length(voltages)
    ,3591,3);
I_DC = zeros(length(bars),length(temperatures),length(voltages));
tanD = zeros(length(bars),length(temperatures),length(voltages)
    ,3591);

for i = 1:length(bars)
    for j = 1:length(temperatures)
        for k = 1:length(voltages)
            mpath = sprintf('%s\\Test1_%s_%dC_%dkV.txt',pathX,
                bars{i},temperatures(j),voltages(k));
            A{i}{j}{k} = readmatrix(mpath,'Range','J:M');

            T = readtable(mpath);
            timeDataX = T(:,9);
            timeDataY{i}{j}{k} = table2array(timeDataX);
            timeData = char(timeDataY{i}{j}{k}); % NB Matlab2020


            for m = 1:size(timeData,1)
                seconds{i}{j}{k}(m) = str2double(timeData(m,1:2))
                    .*60*60+str2double(timeData(m,4:5)).*60+
                    str2double(timeData(m,7:8));
            end

            tmp(:,:) = A{i}{j}{k}(:,1:3);
            Data(i,j,k,1:size(tmp,1),1:3) = tmp;

            tmp2(:) = tmp(:,2);
            tmpPol = tmp2(tmp(:,1)>100);
            tmpDepol = tmp2(tmp(:,1)<100);
            len1 = length(tmpPol);
            len2 = length(tmpDepol);
            len = min(len1, len2);
            tmp3(:) = tmpPol(1:len) - tmpDepol(1:len);


            I_DC(i,j,k) = mean(tmp3(end/2+1:end));%mikroA %
            tmpSeconds(:) = seconds{i}{j}{k};
            tanD(i,j,k,1:length(tmpPol)) = (tmpPol .*1e-6 .*
```

```
                tmpSeconds(1:length(tmpPol)))/(0.63 .* C  .*
                voltages(k) .*1000); %Bruke actual voltage
            tanD2(i,j,k,1:length(tmpDepol)) = (tmpDepol .*1e-6 .*
                 tmpSeconds(1:length(tmpDepol)))/(0.63 .* C  .*
                voltages(k) .*1000);
            Sigma{i}{j}{k} = (e0 .* eR .*I_DC(i,j,k) .* 1e-6)/(
                voltages(k) .*1000 .* C);
            Sigmat{i}{j}{k}(:) = (e0 .* eR .* tmp3.* 1e-6)/(
                voltages(k) .*1000 .* C); %For time dependence
                sigma
            clear tmp tmp2 tmp3
        end
    end
end

%Plotting


colors = [  166,206,227
            31,120,180
            178,223,138
            51,160,44
            251,154,153
            227,26,28
            253,191,111
            255,127,0
            202,178,214
            106,61,154
            255,255,153
            177,89,40
            ]/255;


%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%% Plot the data: %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

markers1 = {'ok' 'sk' 'dk' '^k' 'vk' '<k'};
markers2 = {':ok' ':sk' ':dk' ':^k' ':vk' ':<k'};
markers3 = {'--ok' '---^k' '--dk' '--hk' '--vk' '--<k'};
markers4 = {'-o' '-^' '-d' '-h' '-v' '-<' '--^' '--d' '--h' '--v'
    '--<'};
markers5 = {'-' '--' ':' '-.' '-o'};
```

```

facecolor = [0,1];


%%
%Plotting for comparison before and after thermal cycling below

%%
%Compares pol and depol before and after cycling
%Use only bar before and after for this one

%    for j = 1:length(temperatures)
%        for k = 1: length(voltages)
%
%            figure1 = figure('Position',[20 20 1.5*scrsz(4)*2/3 scrsz(4)*2/3],'PaperSize',[1.5*16 16],'PaperPositionMode', 'auto');
%            hold on
%            tmp2(:) = Data(1,j,k,:,2)*1000; %Endre hvilke data som plottes Data(i,j,k,:,2)
%            tmp3(:) = Data(2,j,k,:,2)*1000;
%
%            tmpSeconds(:) = seconds{i}{j}{k}(:);
%
%            plot(tmpSeconds(1:end/2),tmp2(1:end/2),markers5{1},'LineWidth',2,'Color',colors(2,:),'Markersize',10)
%            plot(tmpSeconds(1:end/2),tmp3(1:end/2),markers5{2},'LineWidth',2,'Color',colors(2,:),'Markersize',10)
%            plot(tmpSeconds(1:end/2),tmp2(end/2+1:end),markers5{1},'LineWidth',2,'Color',colors(5,:),'Markersize',10)
%            plot(tmpSeconds(1:end/2),tmp3(end/2+1:end),markers5{2},'LineWidth',2,'Color',colors(5,:),'Markersize',10)
%            ylabel('$I_{POL/DEPOL}$ (nA)')
%            xlabel('Time [s]')
%
%            set(gca,'YMinorTick','on','YScale','log')%,'YTick',[0.1 1 10 100 1000]);
%            set(gca,'XMinorTick','on','XScale','log')%,'XTick',[0.1 1 10 100 1000],'XTickLabel',{' ',' ',' ',' ',' '});
%            set(gca,'FontSize',5*20/figureWidth);
%            Tittel = sprintf ('%s %d %s%s %d %s', 'Polarization and Depolarization current', temperatures(j), 'C',char(176) , voltages(k), 'kV');
```

```
%             title(Tittel)
%             legend('O162B Pol Before Cycling','O162B Pol After Cycling','O162B Depol Before Cycling','O162B Depol After Cycling','Location','NorthEast');
%             legend('boxoff')
%             grid on
%
%
%         end
%     end

%%


%%
%Plots several bars pol


%     for j = 1:length(temperatures)
%         for k = 1: length(voltages)
%
%             figure1 = figure('Position',[20 20 1.5*scrsz(4)*2/3 scrsz(4)*2/3],'PaperSize',[1.5*16 16],'PaperPositionMode', 'auto');
%             hold on
%             tmp2(:) = Data(1,j,k,:,2)*1000; %Endre hvilke data som plottes Data(i,j,k,:,2)
%             tmp3(:) = Data(2,j,k,:,2)*1000;
%             tmp4(:) = Data(3,j,k,:,2)*1000;
%             tmp5(:) = Data(4,j,k,:,2)*1000;
%             tmp6(:) = Data(5,j,k,:,2)*1000;
%             tmp7(:) = Data(6,j,k,:,2)*1000;
%             tmpSeconds(:) = seconds{i}{j}{k}(:);
%
%             plot(tmpSeconds(1:end/2),tmp2(1:end/2),markers5{1},'LineWidth',2,'Color',colors(1,:),'Markersize',10)
%             plot(tmpSeconds(1:end/2),tmp3(1:end/2),markers5{2},'LineWidth',2,'Color',colors(1,:),'Markersize',10)
%             plot(tmpSeconds(1:end/2),tmp4(1:end/2),markers5{1},'LineWidth',2,'Color',colors(3,:),'Markersize',10)
%             plot(tmpSeconds(1:end/2),tmp5(1:end/2),markers5{2},'LineWidth',2,'Color',colors(3,:),'Markersize',10)
%             plot(tmpSeconds(1:end/2),tmp6(1:end/2),markers5
```

```
{1},'LineWidth',2,'Color',colors(6,:),'Markersize',10)
%            plot(tmpSeconds(1:end/2),tmp7(1:end/2),markers5{2},'LineWidth',2,'Color',colors(6,:),'Markersize',10)
%            ylabel('$I_{POL}$ (nA)')
%            xlabel('Time [s]')
%
%            set(gca,'YMinorTick','on','YScale','log')%,'YTick',[0.1 1 10 100 1000]);
%            set(gca,'XMinorTick','on','XScale','log')%,'XTick',[0.1 1 10 100 1000],'XTickLabel',{' ',' ',' ',' ',' '});
%            set(gca,'FontSize',5*20/figureWidth);
%            Tittel = sprintf ('%s %d %s%s %d %s', 'Polarization current', temperatures(j), 'C',char(176) , voltages(k), 'kV');
%            title(Tittel)
%            legend('O117B Before Cycling','O117B After Cycling','O162B Before Cycling','O162B After Cycling', 'O163B Before Cycling','O163B After cycling','Location','NorthEast');
%            legend('boxoff')
%            grid on
%
%
%        end
%    end
%%%

%Plots DC current for all bars in the same plot

%    for j = 1:length(temperatures)
%        for k = 1:length(voltages)
%
%            figure2 = figure('Position',[20 20 1.5*scrsz(4)*2/3 scrsz(4)*2/3],'PaperSize',[1.5*16 16],'PaperPositionMode', 'auto');
%            hold on
%            tmp2(:) = Data(1,j,k,:,2)*1000;
%            tmp3(:) = Data(2,j,k,:,2)*1000;
%
%            tmp4(:) = Data(3,j,k,:,2)*1000;
%            tmp5(:) = Data(4,j,k,:,2)*1000;
%            tmp6(:) = Data(5,j,k,:,2)*1000;
%            tmp7(:) = Data(6,j,k,:,2)*1000;
%
```

```
%
%           tmpSeconds(:) = seconds{i}{j}{k}(:);
%           plot(tmpSeconds(1:end/2),tmp2(1:end/2)-tmp2(end/2+1:end),markers5{1},'LineWidth',2,'Color',colors(2,:),'Markersize',10)
%           plot(tmpSeconds(1:end/2),tmp3(1:end/2)-tmp3(end/2+1:end),markers5{2},'LineWidth',2,'Color',colors(2,:),'Markersize',10)
%
%           plot(tmpSeconds(1:end/2),tmp4(1:end/2)-tmp4(end/2+1:end),markers5{1},'LineWidth',2,'Color',colors(4,:),'Markersize',10)
%           plot(tmpSeconds(1:end/2),tmp5(1:end/2)-tmp5(end/2+1:end),markers5{2},'LineWidth',2,'Color',colors(4,:),'Markersize',10)
%           plot(tmpSeconds(1:end/2),tmp6(1:end/2)-tmp6(end/2+1:end),markers5{1},'LineWidth',2,'Color',colors(6,:),'Markersize',10)
%           plot(tmpSeconds(1:end/2),tmp7(1:end/2)-tmp7(end/2+1:end),markers5{2},'LineWidth',2,'Color',colors(6,:),'Markersize',10)
%
%           ylabel('$I_{DC}$ [nA]')
%           xlabel('Time [s]')
%           Tittel = sprintf ('%s %d %s%s %d %s','DC current',temperatures(j), 'C',char(176) , voltages(k), 'kV');
%           title(Tittel)
%           grid on
%           set(gca,'YMinorTick','on','YScale','log')%,'YTick',[0.1 1 10 100 1000]);
%           set(gca,'XMinorTick','on','XScale','log')%,'XTick',[0.1 1 10 100 1000],'XTickLabel',{' ',' ',' ',' ',' '});
%           set(gca,'FontSize',5*20/figureWidth);
%           legend('O117B Before Cycling','O117B After Cycling','O162B Before Cycling','O162B After Cycling','O163B Before Cycling','O163B After Cycling','Location','NorthEast');
%           legend('boxoff')
%
%       end
%   end
%%

%%
```

```
%Plots several tan delta as function of frequency/time pol


%     for j = 1:length(temperatures)
%         for k = 1:length(voltages)
%
%             figure6 = figure('Position',[20 20 1.5*scrsz(4)*2/3 scrsz(4)*2/3],'PaperSize',[1.5*16 16],'PaperPositionMode', 'auto');
%             hold on
%             tmp7(:) = tanD(1,j,k,:);
%             tmp8(:) = tanD(2,j,k,:);
%             tmp9(:) = tanD(3,j,k,:);
%             tmp10(:) = tanD(4,j,k,:);
%             tmp11(:) = tanD(5,j,k,:);
%             tmp12(:) = tanD(6,j,k,:);
%
%             tmpSeconds(:) = seconds{i}{j}{k}(:);
%
%             plot(0.1./tmpSeconds(1:length(tmpPol)),tmp7(1:length(tmpPol)),markers5{1},'LineWidth',2,'Color',colors(2,:),'Markersize',10)
%             plot(0.1./tmpSeconds(1:length(tmpPol)),tmp8(1:length(tmpPol)),markers5{2},'LineWidth',2,'Color',colors(2,:),'Markersize',10)
%             plot(0.1./tmpSeconds(1:length(tmpPol)),tmp9(1:length(tmpPol)),markers5{1},'LineWidth',2,'Color',colors(4,:),'Markersize',10)
%             plot(0.1./tmpSeconds(1:length(tmpPol)),tmp10(1:length(tmpPol)),markers5{2},'LineWidth',2,'Color',colors(4,:),'Markersize',10)
%             plot(0.1./tmpSeconds(1:length(tmpPol)),tmp11(1:length(tmpPol)),markers5{1},'LineWidth',2,'Color',colors(6,:),'Markersize',10)
%             plot(0.1./tmpSeconds(1:length(tmpPol)),tmp12(1:length(tmpPol)),markers5{2},'LineWidth',2,'Color',colors(6,:),'Markersize',10)
%             ylabel('$tan(\delta)$')
%             xlabel('Frequency [Hz]')
%             Tittel = sprintf ('%d %s%s %d %s', temperatures(j), 'C',char(176) , voltages(k), 'kV');
%             title(Tittel)
%             grid on
```

```
%             legend('O117B Before Cycling','O117B After  Cycling','O162B Before Cycling','O162B After  Cycling','O163B Before Cycling','O163B After  Cycling','Location', 'NorthEast')
%             set(gca,'YMinorTick','on','YScale','log')%,'YTick',[0.1 1 10 100 1000]);
%             set(gca,'XMinorTick','on','XScale','log')%,'XTick',[0.1 1 10 100 1000],'XTickLabel',{' ',' ',' ',' ',' '});
%             set(gca,'FontSize',5*20/figureWidth);
%
%         end
%     end

%%


%%
%Plots several tan delta as function of frequency/time Depol


%     for j = 1:length(temperatures)
%         for k = 1:length(voltages)
%
%             figure6 = figure('Position',[20 20 1.5*scrsz(4)*2/3 scrsz(4)*2/3],'PaperSize',[1.5*16 16],'PaperPositionMode', 'auto');
%             hold on
%             tmp7(:) = tanD2(1,j,k,:);
%             tmp8(:) = tanD2(2,j,k,:);
%             tmp9(:) = tanD2(3,j,k,:);
%             tmp10(:) = tanD2(4,j,k,:);
%             tmp11(:) = tanD2(5,j,k,:);
%             tmp12(:) = tanD2(6,j,k,:);
%
%             tmpSeconds(:) = seconds{i}{j}{k}(:);
%
%             plot(0.1./tmpSeconds(1:length(tmpDepol)),tmp7(1:length(tmpDepol)),markers5{1},'LineWidth',2,'Color',colors(2,:),'Markersize',10)
%             plot(0.1./tmpSeconds(1:length(tmpDepol)),tmp8(1:length(tmpDepol)),markers5{2},'LineWidth',2,'Color',colors(2,:),'Markersize',10)
%             plot(0.1./tmpSeconds(1:length(tmpDepol)),tmp9(1:length(tmpDepol)),markers5{1},'LineWidth',2,'Color',colors
```

```
(4,:),'Markersize',10)
%            plot(0.1./tmpSeconds(1:length(tmpDepol)),tmp10(1:length(tmpDepol)),markers5{2},'LineWidth',2,'Color',colors(4,:),'Markersize',10)
%            plot(0.1./tmpSeconds(1:length(tmpDepol)),tmp11(1:length(tmpDepol)),markers5{1},'LineWidth',2,'Color',colors(6,:),'Markersize',10)
%            plot(0.1./tmpSeconds(1:length(tmpDepol)),tmp12(1:length(tmpDepol)),markers5{2},'LineWidth',2,'Color',colors(6,:),'Markersize',10)
%            ylabel('$tan(\delta)$')
%            xlabel('Frequency [Hz]')
%            Tittel = sprintf ('%d %s%s %d %s', temperatures(j), 'C',char(176) , voltages(k), 'kV');
%            title(Tittel)
%            grid on
%            legend('O117B Before Cycling','O117B After Cycling','O162B Before Cycling','O162B After Cycling','O163B Before Cycling','O163B After Cycling','Location', 'NorthEast')
%            set(gca,'YMinorTick','on','YScale','log')%,'YTick',[0.1 1 10 100 1000]);
%            set(gca,'XMinorTick','on','XScale','log')%,'XTick',[0.1 1 10 100 1000],'XTickLabel',{' ',' ',' ',' ',' '});
%            set(gca,'FontSize',5*20/figureWidth);
%
%        end
%    end
%%

%%
%Plots tanDelta (Pol) as function of temperature for several voltages


% figure5 = figure('Position',[20 20 1.5*scrsz(4)*2/3 scrsz(4)*2/3],'PaperSize',[1.5*16 16],'PaperPositionMode', 'auto');
% hold on
%    %for k=1:length(voltages)
%
%        for j=1:length(temperatures)
%            tmp6(j) = tanD(1,j,3, 600); %M  velge ut noen tidspunkter av interesse
%            tmp7(j) = tanD(2,j,3, 600);
```

```
%           end
%
%
%           plot(temperatures,tmp6,markers5{1},'LineWidth',2,'Color',colors(2,:),'Markersize',10)
%           plot(temperatures,tmp7,markers5{2},'LineWidth',2,'Color',colors(2,:),'Markersize',10)
%
%
%     %end
%           ylabel('tan($\delta$)')
%           xlabel('Temperature ($^oC$)')
%           set(gca,'YMinorTick','on','YScale','log')%,'YTick',[0.1 1 10 100 1000]);
%           set(gca,'XMinorTick','on','XScale','lin')%,'XTick',[0.1 1 10 100 1000],'XTickLabel',{' ',' ',' ',' ',' '});
%           set(gca,'FontSize',5*20/figureWidth);
%
%      grid on
%      legend('O117B Before Cycling','O117B After Cycling', 'Location','SouthEast')
%      Tittel = sprintf('%s og %s',bars{1},bars{2});
%      title(Tittel)

%%%


%%%

%%%
%DC conductivity as a function of temp

%      figure7 = figure('Position',[20 20 1.5*scrsz(4)*2/3 scrsz(4)*2/3],'PaperSize',[1.5*16 16],'PaperPositionMode', 'auto');
%     %for i = [1,2]
%      hold on
%     %for k = 1:length(voltages)
%
%           for j = 1:length(temperatures)
%               tmp8(j) = Sigma{1}{j}{3};
%               tmp9(j) = Sigma{2}{j}{3};
%
%           end
```

```
%
%         plot(temperatures,tmp8,markers5{1},'LineWidth',2,'Color',colors(2,:),'Markersize',10)
%         plot(temperatures,tmp9,markers5{2},'LineWidth',2,'Color',colors(2,:),'Markersize',10)
%
%
%     %end
%
%         ylabel('DC conductivity $\sigma$ [S/m]','interpreter','latex')
%         xlabel('Temperature ($^oC$)')
%         set(gca,'YMinorTick','on','YScale','log')%,'YTick',[0.1 1 10 100 1000]);
%         set(gca,'XMinorTick','on','XScale','lin')%,'XTick',[0.1 1 10 100 1000],'XTickLabel',{' ',' ',' ',' ',' '});
%         set(gca,'FontSize',5*20/figureWidth);
%
%     grid on
%     legend('O117B Before Cycling','O117B After Cycling', 'Location','SouthEast')
%     Tittel = sprintf('%s og %s',bars{1},bars{2});
%     title(Tittel)
%%

%%
%Plots DC conductivity as a function of time

% len1 = length(tmpPol);
% len2 = length(tmpDepol);
% len = min(len1, len2);
%
%     for j = 1:length(temperatures)
%         for k = 1:length(voltages)
%
%             figure6 = figure('Position',[20 20 1.5*scrsz(4)*2/3 scrsz(4)*2/3],'PaperSize',[1.5*16 16],'PaperPositionMode', 'auto');
%             hold on
%             tmp7(:) = Sigmat{1}{j}{k}(:);
%             tmp8(:) = Sigmat{2}{j}{k}(:);
%             tmp9(:) = Sigmat{3}{j}{k}(:);
%             tmp10(:) = Sigmat{4}{j}{k}(:);
```

```
%             tmp11(:) = Sigmat{5}{j}{k}(:);
%             tmp12(:) = Sigmat{6}{j}{k}(:);
%             tmpSeconds(:) = seconds{i}{j}{k}(:);
%
%             plot(tmpSeconds(1:len),tmp7(1:len),markers5{1},'LineWidth',2,'Color',colors(2,:),'Markersize',10)
%             plot(tmpSeconds(1:len),tmp8(1:len),markers5{2},'LineWidth',2,'Color',colors(2,:),'Markersize',10)
%             plot(tmpSeconds(1:len),tmp9(1:len),markers5{1},'LineWidth',2,'Color',colors(3,:),'Markersize',10)
%             plot(tmpSeconds(1:len),tmp10(1:len),markers5{2},'LineWidth',2,'Color',colors(3,:),'Markersize',10)
%             plot(tmpSeconds(1:len),tmp11(1:len),markers5{1},'LineWidth',2,'Color',colors(6,:),'Markersize',10)
%             plot(tmpSeconds(1:len),tmp12(1:len),markers5{2},'LineWidth',2,'Color',colors(6,:),'Markersize',10)
%
%             ylabel('DC conductivity $\sigma$ [S/m]','interpreter','latex')
%             xlabel('Time [s]')
%             Tittel = sprintf('%d %s%s %d %s', temperatures(j), 'C',char(176) , voltages(k), 'kV');
%             title(Tittel)
%             grid on
%             legend('O117B Before Cycling', 'O117B After Cycling', 'O162B Before Cycling', 'O162B After Cycling', 'O163B Before Cycling', 'O163B After Cycling' ,'Location', 'Northeast')
%             set(gca,'YMinorTick','on','YScale','log')%,'YTick',[0.1 1 10 100 1000]);
%             set(gca,'XMinorTick','on','XScale','log')%,'XTick',[0.1 1 10 100 1000],'XTickLabel',{' ',' ',' ',' ',' '});
%             set(gca,'FontSize',5*20/figureWidth);
%
%         end
%     end
```

Daniel Ekornrud Fjeldstad

NTNU
Kunnskap for en bedre verden