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Comparative Analysis of the Dielectric Performance of Insulating Liquids Aged Under Different Conditions

Master's thesis in Sustainable Electric Power Engineering and Electromobility

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Testing Performance Deterioration due to Aging in Custom Transformer Tanks Used for Radar Applications in kHz Square Wave Operation

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Abstract

This thesis investigates the dielectric performance of transformer oils used as high voltage insulation media in membrane-sealed and fully enclosed transformers and compares the impact of the sealing methods. Oil samples were collected from real transformer units, which were operating under different conditions over several years and the insulating oils in them were exposed to combined electrical-thermal stresses of different duration and intensity. It was anticipated that the intake of air through the sealings of the transformer tanks might initiate chemical reactions under such stresses thus causing accelerated ageing of the insulation. To examine this hypothesis, dielectric measurements and breakdown tests were conducted according to the respective standards. The former included measurements of complex capacitances, loss factor and oil resistivity whereas the latter provided the maximum electric field strength the oil could withstand. The obtained results indicate a rapid initial degradation in some of the measured parameters, while the evidence for storage-time-dependent degradation remains inconclusive. Under the applied test conditions, the oil samples taken from fully enclosed transformer tank showed a slightly better performance than those from membrane-sealed tank. To explicate this finding, an attempt to correlate the measured results with the histories of the respective transformer units is undertaken. Ageing factors affecting performance of the insulating oils, including chemical degradation under electro-thermal stresses and possible contaminations, are discussed based on the performed literature study.

Keywords: Transformer oil, membrane seal, high frequency square wave, electrical insulation, oil degradation.

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1
Introduction

Transformers are a crucial part of electrical systems. Their role is to transform the voltage to a different level than it was generated at. They are used in a variety of industries at any type of voltage level. High voltage levels introduce a risk of failure due to electrical breakdown. To keep the transformers operating in a optimal thermal range and protect from electrical breakdowns transformer oil is used.

This thesis aims to investigate how various factors impact and age the transformer oil used in small high voltage transformers for radar applications at SAAB and how the aging affects performance of the transformers used. The transformers are used to supply higher voltage to the sending antennas and are used in a variety of environments which can age the transformer oil differently.

1.1 Background

Transformers and other high voltage equipment are often submerged in oil for electrical isolation and thermal management. The insulating oil protects it from electrical breakdown between the transformer tank and the electrical components and provides a medium for heat to dissipate through. Over its lifetime the oil can interact with the surrounding materials like the electronics, tank walls and in some cases air in the environment. These interactions occur both during static conditions when the transformer is turned off, and when high voltage stresses are applied. These interactions can over time have severe effects on the oil's insulating performance. To ensure high quality of the insulation and long lifespan, factors affecting its performance under given conditions should be evaluated.

In radar applications, transformers are used in order to transform square wave electrical pulses to transmitting antennas in the radar systems that uses higher voltage to increase the power to allow long range detection. The signals range in scale up to 15-30 kV and in the pulse frequency range of 1-40 kHz with a very fast rise time quite a bit shorter than 1 μs. Signs of performance deterioration have been observed in previous transformers with non fully metallic transformer tanks by the manufacturer SAAB. With a new smaller transformer tank design implemented using a membrane seal to handle pressure differences that arise from working in various environments. Initial testing has shown that the membrane allows helium enter the tank. Therefore, the effect of age on electrical performance in this transformer tanks are investigated in this thesis and is compared to an older sample without this membrane seal.

1.2 Aim

This thesis aims to investigate differences in performance of transformer oil of different ages from customized transformer tanks. The investigation is performed by measuring breakdown strength, conductivity, permittivity, and the loss factor $tan(\delta)$. These properties are compared between samples from the new specialized membrane-sealed transformer tank and an older bellows-sealed transformer tank to asses wether the test samples remain above the specified criterion under the applied lab test conditions.

In addition, the thesis aim to provide possible mechanisms of aging in the tanks through a literature study to interpret the results of the measurements.

This work is performed together with SAAB AB, who provides the oil samples.

1.3 Objectives

This work:

- Determines and compares the performance variation of differently aged transformer oil from the new tank design and a bellows-sealed design, by measuring conductivity, permittivity, breakdown strength, and $\tan(\delta)$.
- Evaluates how and if these electrical properties change with age and identifies which properties are most significantly affected.
- Answers at what point the oil is no longer provides adequate electrical insulation. The limit were based on internal design parameters from the transformer tank manufacturer SAAB.
- Provide possible reasons for the loss of performance.

1.4 Limitations

The scope of this work is subject to several limitations:

- The analysis is limited to electrical performance. Therefore mechanical and chemical properties are not investigated. As no chemical analysis is performed, the presence and types of contaminants in the oil cannot be directly determined.
- The availability of test samples is limited by the number of units provided by SAAB. Consequently, the samples are grouped by nominal age, but differences in operational history may affect the results. This introduces a risk of outliers, which may influence the results and limit the ability to draw definitive conclusions.
- Due to the complexity and fast rise time of the operational signal, it is not feasible within the time and budget constraints of this project to replicate the exact conditions. Therefore, aging effects are evaluated using lower frequencies and simpler signal shapes. This allows detection of aging but not explaining the behavior under actual operating conditions.

- The transformer oil samples provided by SAAB consist primarily of prototypes and one production unit. Because of this the samples have undergone different test durations that vary between 10–100 hours. These tests are not all documented so variations in operational exposure may therefore affect the measurements, particularly if electrical stress is a dominant aging mechanism. The samples are however still treated as representative of their respective aging levels to enable comparative analysis.

2
Theory

This chapter presents the electrical properties studied in this thesis, examines how they are affected over time by different aging mechanisms, and outlines how to derive the parameters from standardized test methods.

2.1 Electrical performance parameters for transformer oil

The electrical properties that are best used to assess the aging of insulation oil include conductivity, permittivity, dissipation factor, and breakdown strength [1]. Accordingly, this thesis focuses on these parameters in the conducted tests.

2.1.1 Conductivity

In liquid insulation, conductivity generally refers to the steady state DC conductivity [2]. Conductivity in liquids is governed by the concentration of charge carriers and their mobility in the medium. The number of carriers depends on, for example, the number of pollutants, whether applied voltage is sufficient to ionize atoms, and amount of carriers inherent in the liquid [2].

To accurately measure conductivity, capacitive transients must first decay to ensure steady-state conditions. Therefore, the duration of the applied voltage v must be such that only the steady-state current i is measured. Once steady-state conditions have been reached, the system can be considered purely resistive, and Equation 2.1 can be used to derive the conductivity by removing the geometrical influences from the measured resistance R [3]. Where $\mathbf{J}$ represents the current density of the oil, σ the conductivity, and $\mathbf{E}$ the applied electric field.

$$R = \frac{v}{i} \Rightarrow \sigma = \frac{\mathbf{J}}{\mathbf{E}} \tag{2.1}$$

External factors such as temperature, pressure, water contamination, and other contaminants may increase the conductivity of the insulation oil. Water is the most common contaminant and has a comparatively high conductivity of $\sigma = 10^{-4}, \mathrm{S/m}$. As a result, it creates conductive paths within the medium, thereby lowering the overall resistivity of the insulation [2]. Apart from water, other contaminants include particles from tank walls and solid insulation materials present in the oil. These solid particles may form conductive bridges within the insulation material, creating weak spots [2].

The material conductivity can be expressed in terms of ion concentration using Equation 2.2, where n denotes the number of ions, q the electric charge, and μ the average mobility [4].

$$\sigma = n * q * \mu \tag{2.2}$$

The conductivity of the material depends on the ambient temperature. An increase in temperature increases ion mobility and the number of charge carriers. The relationship between conductivity and temperature can be described using the Arrhenius Equation 2.3, where W represents the activation energy, T is the absolute temperature and k is the Boltzmann constant [2].

$$\sigma = \sigma_0 * e^{-W/kT} \tag{2.3}$$

The effect of temperature can also be observed in tests performed in [1], which showed that samples heated to different temperatures and subjected to similar electrical stresses showed a decrease in resistance with increasing temperature.

Furthermore, as mentioned previously, the applied voltage affects the conductivity. If a sufficiently high voltage is applied to the insulation material, the resulting electric field may inject charge carriers from the cathode or via dissociation processes [2]. This relationship was also tested in [1] where each sample was tested at several voltage levels and showed a decrease in resistivity with increasing applied voltage.

2.1.2 Permittivity

Aside from conductivity, the permittivity of the insulation liquid is also important [2]. The permittivity describes the ability of the material to polarize under an applied electric field. Similar to conductivity, permittivity depends on several factors, including operating frequency and temperature. Contaminants may also increase the permittivity by introducing localized polarization differences and field enhancement within the insulation material [2].

The frequency dependence of the permittivity is governed by several polarization mechanisms, including interfacial, orientational, lattice, and atomic polarization [2]. The polarization mechanisms generate internal fields that influence the electric field distribution within the material.

Interfacial polarization occurs at the lowest frequencies where charge carriers accumulate between two interfaces with different conductivity.

The orientational polarization occurs at slightly higher frequency where molecular dipoles align with the applied electric field from an initially disordered state.

Lattice polarization mainly occurs in crystalline materials, where polarized particles distort the crystal lattice structure. Since transformer oil is a liquid and lacks a crystalline structure, this mechanism is considered negligible.

Atomic polarization occurs at particularly high frequencies, where the applied electric field distorts the electron distribution relative to the atomic nucleus [2].

The temperature dependence is primarily governed by the orientational polarization [2]. As the mobility increases with temperature, the ability of molecules to align with the electric field improves consequently. In certain cases, the interfacial polarization may also exhibit similar temperature dependence. In [5], frequency-domain spectroscopy was performed at 23° C, 50° C, and 80° C, demonstrating an increase in permittivity with increasing temperature.

Similar to conductivity, the permittivity is influenced by pollutants. Since contaminants may possess different electrical properties than the insulation oil, they can alter the dielectric behavior of the insulation system. For example, water's high relative permittivity of $\varepsilon_r = 81$ [2]. This affects capacitance of the insulation and introduces localized field enhancements around the contaminants [2].

Furthermore, the permittivity can be represented as a real ε' and imaginary ε'' component [2]. In this representation ε' represents the capacitive response of the material and ε'' represents the dielectric losses associated with polarization. This separation is commonly used when characterizing insulation materials to distinguish between capacitive behavior and dielectric losses.

2.1.3 Dissipation factor

A key aspect of insulation mediums is the relation between dielectric losses and charge accumulation. The real and imaginary parts are both measured during the permittivity tests the dissipation factor is then calculated using Equations 2.4, 2.5 and 2.6. Here $\tan(\delta_L)$ is the conductive losses and $\tan(\delta_{Pol})$ is the polarization losses [2]. A high value of $\tan(\delta)$ indicates increased dielectric losses within the insulation material, meaning that a larger portion of the electrical energy is dissipated as heat. In transformer insulation systems, increased dissipation factor is commonly associated with aging through moisture, contamination, and degradation of the solid insulation [2].

$$\tan(\delta) = \tan(\delta_L) + \tan(\delta_{Pol}) \tag{2.4}$$

$$\tan(\delta_L) = \frac{\sigma}{\omega * \varepsilon_0 * \varepsilon_r'} \tag{2.5}$$

$$\tan(\delta_{Pol}) = \frac{\varepsilon_r''}{\varepsilon_r'} \tag{2.6}$$

2.1.4 Dielectric strength

The dielectric strength is a measure of how well a material's ability to withstand electric stress before an electric breakdown occurs. Since electric breakdown is an inherently stochastic phenomenon, predicting exactly at what voltage breakdown occurs is not possible. The dielectric strength of insulation oil is influenced by several parameters, including but not exclusively geometrical configuration, water content, stressed volume, oil convection, breakdown mechanism. Due to the large number of influencing parameters there is no established mathematical model accurately describing dielectric breakdown in liquids. The effects of these parameters have largely been established through empirical studies [2].

The breakdown mechanism that occurs depends on several influencing parameters. In very clean with minimal pollutants, moisture, and with a highly uniform applied electric field, intrinsic breakdown will be the dominant mechanism [2]. However, since these conditions are very rare, streamer breakdown is more common. Streamers can develop through distortion of the electric field around gas bubbles , water droplets or pollution particles, leading to space charge regions and partial breakdowns. If the applied field is sufficiently strong, these processes can propagate through the material through electron avalanche propagation.

The breakdown voltage depends on the presence and distribution of contaminants within the stressed volume. As the electrically stressed volume increases, the probability of defects such as moisture, gas bubbles, or particles also increases, leading to a reduction in the effective dielectric strength. However, the breakdown voltage does not scale linearly with volume, since it also depends on electrode spacing and field distribution.

2.2 Ageing mechanisms in oil

2.2.1 Electrical stresses impact on insulation aging

During operation there are several factors that affect aging, such as voltage level, frequency, and rise time.

In a study by Devadiga and Jayaram [6] the impact of frequency and rise time on insulation oil aging was investigated. First, the aging time dependence was evaluated and the performance continuously decreased under operation up to 130 h. It was also found to saturate thereafter with little difference between samples aged for 130 and 300 h. In the frequency-dependence tests, samples were aged for 130 h using frequencies of either 1 or 3 kHz and a rise time of either 200 or 650 ns with a voltage amplitude of 6 kV. The results from the studies show both an accelerated aging with increasing frequency or decreasing rise time [6].

Khanali and Jayaram [7] investigated how the rise time and voltage affect the energy of the partial discharges (PDs). The study showed that shorter rise times were associated with an increased PD inception voltage, resulting in a higher PD energy during discharges. In tests where PDs occurred across all tested rise times, those generated at the shortest rise times resulted a higher concentration of hydrogen in the test samples. Accumulated hydrogen gas in the transformer oil is a positive feedback mechanism, since an increased hydrogen concentration increases the risk of further PDs which in turn may release more hydrogen [8]. As the PD severity increases the risk for a complete electrical breakdown also increases, which is more detrimental to transformer operation.

2.2.2 Ambient factors impact on insulation aging

Aging due to high surrounding temperature can affect the insulation properties of transformer oil as elevated temperatures accelerate aging through oxidation and increased moisture absorption [9]. Thermal aging tests performed in [9] showed reduced dielectric strength and resistivity as the main indicators of thermal aging. Since the oil is partially used for cooling there is some heating of the oil which can cause thermal aging. As oil is subjected to higher temperatures the water content increased substantially which is related to reduced insulation performance [10]. Since the chemical compounds in the oil changes with time the ambient temperature is an accelerating factor.

In the case of non fully sealed transformer tank another environmental factor is the gas composition, since gases such as N_2, H_2O and O_2 may diffuse into the oil from the surrounding air. The diffusion rate is dependent on ambient pressure [11], where a higher pressure increases the amount of dissolved gas in the oil. Issues can arise when excited oxygen molecules dissociate into atoms. These oxygen atoms are highly reactive and may react with other substances in the oil [11]. In addition to gaseous contaminants there may also be residues from other components, such as copper oxide formed through reactions between the copper windings and oxygen.

2.3 Aging mechanisms under non-standard operating conditions

A major distinction in the operating conditions of this transformer oil is the fact that the tank is not fully airtight. The tank is sealed using a membrane to prevent oil leakage and compensate for pressure variations caused by thermal expansion and ambient pressure. This membrane, however, has been shown to be permeable to gases. Therefore, aging due to dissolved gases in the oil is possible. Inclusion of dissolved gases can contribute to lower breakdown strength of the oil and increased dielectric losses. Gas inclusions in the insulation can also contribute to accelerated aging due to other phenomena such as partial discharges in the oil. If the gas accumulates in the form of bubbles, the dielectric strength inside the bubbles is lower than in the surrounding oil. As a result, electrical breakdown may occur inside the bubbles, leading to localized heating and increased thermal stress on the insulation material.

The key function of the membrane is to compensate for thermal expansion, thereby reducing mechanical stresses on the tank walls. However, the presence of the membrane may lead to internal pressure variations in the oil. This reduces insulation performance as decreased pressure reduces inception voltage for both PDs and complete electrical breakdown. The reduction in pressure increase the mean free path of free electrons resulting in a higher likelihood of electron avalanche processes and in turn PDs or complete breakdown.

The membrane is made of fluorosilicone. Internal tests at SAAB have shown that the seal permits permeation of gas. The process is described in [12]. The factors affecting increased diffusion include pressure difference, temperature, thickness and area. The study shows the diffusion rate of different gases through fluorosilicone as well as other materials. The rates of diffusion indicate what types of gases are likely to be more prevalent in the oil as a result of diffusion. Chemical studies could, together with tests performed in this thesis, provide an estimation of how long it would take to reach conditions unsuitable for safe operation through this method. The chemical analysis could determine at what concentration of dissolved gases the electrical parameters fall below acceptable limits and then determine how long it would take to diffuse that amount of gas through the membrane. However, since this is outside the scope of this thesis, the chemical tests will not be discussed further.

The voltage waveform in this application differs from conventional 50 Hz sinusoidal operation. Instead, a high-frequency square wave of 1-5 kHz is utilized. As mentioned in 2.2.1, risk for PDs increases under square-wave operation and shorter rise times further increasing risk [6, 7]. However, in this transformer application the vast majority of the transformer's lifetime will be spent in storage. Aging due to stresses from the applied waveform will therefore primarily occur during quality tests performed on the units. After testing, the transformers remain unenergized for up to 30 years before use. With this in mind, samples that have been quality tested for a similar duration will exhibit similar aging as a result of electrical stress and not expected to diverge significantly during storage since the transformer has been unenergized. This assumes no other significant aging mechanisms are active during storage.

2.4 Dielectric testing principle

2.4.1 Overview of dielectric response testing

For testing the dielectric response of an insulating material a capacitor is constructed. This capacitor, for liquid insulating materials, is typically implemented using a test cell that contains the liquid between the walls of two concentric cylinders. In the ideal case the resistance of the dielectric is infinite which leads to current leading the voltage by 90°. In practice, no insulator has an infinite resistivity which means a deviation from the ideal phase angle will be observed. This introduces dielectric losses which can be modeled as an equivalent circuit of a series or parallel RC circuit. When there are multiple conduction mechanisms, dielectric losses can be modeled as a combination of series and parallel RC circuits. The loss factor, $\tan(\delta)$ is calculated using Equation 2.7.

$$\tan(\delta) = \frac{P}{Q} = \frac{I_R}{I_C} = \frac{X_C}{R} = \frac{1}{\omega * C * R} \tag{2.7}$$

The most common method for determining dielectric response of an insulation material is the Schering bridge shown in Figure 2.1 [13]. The Schering bridge uses a variable capacitance and resistance to balance the circuit so that no current flows in the middle detector branch. This indicates that the bridge is balanced. When the bridge is balanced, the remaining unknown variables in the circuit are the test object's parameters which can then be calculated since the two legs have the same impedance. The capacitance and loss factor $\tan(\delta)$ are then determined for the test object.

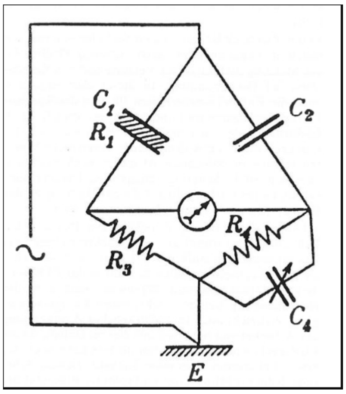


Figure 2.1: A high voltage Schering bridge [14].

The Schering bridge determines the complex capacitance which has both a real and an imaginary part. To determine these components it must first be determined whether resistive or capacitive behavior dominates. This is evaluated in the high-frequency limit. As the frequency approaches infinity if the imaginary part of the capacitance approaches zero and the real part remains constant then capacitive dominates. For this behavior the capacitances are calculated using Equation 2.8 where C' and C'' are the real and imaginary capacitances respectively and this behavior signals that a parallel circuit model is suitable to use for the insulator.

$$C' = C, \quad C'' = \frac{1}{\omega R} \tag{2.8}$$

Whereas if resistive behavior dominates a series model is more applicable and the capacitances are instead calculated using Equation 2.9.

$$C' = \frac{1}{\frac{1}{C} + C(\omega R)^2}, \quad C'' = \frac{\omega R}{\frac{1}{C^2} + (\omega R)^2} \tag{2.9}$$

The equipment used in this lab, the IDAX 300, performs these calculations and provides the complex capacitance and tan(δ) as a function of frequency. An increase in the loss factor implies an increase in losses that degrade dielectric performance of the insulation material. These losses generally appear as heating within the insulation.

The IDAX 300 has a frequency range of up to 10 kHz sinusoidal waveform, this is much lower than the effective operating frequency of the operational signal in the transformer. However, since the goal of the thesis is to compare the intrinsic aging the relative low-frequency dielectric response may be used as an indicator of aging, but it may not fully represent the behavior under fast square-wave stresses. As many of the dominant aging mechanisms are contaminants that originate from operation or manufacturing defects some contamination related aging mechanisms may be visible in the tested frequency range.

Once the capacitance has been determined the relative permittivity may then be calculated. This is obtained as the ratio between the capacitance between the empty test cell and the oil-filled test cell as seen in Equation 2.10.

$$\varepsilon_{oil} = \frac{C_{oil}}{C_{air}} \tag{2.10}$$

The same procedure is applied for both parts of the complex capacitance to calculate the complex permittivity.

2.4.2 Resistivity and conductivity measurement methods

The test measures voltage and current across the test sample to calculate the conductivity. To accomplish this, the system in the test equipment uses Equation 2.11. Here, d is the distance between electrodes, A represents the surface area of the electrodes facing each other and R is the measured resistance.

$$\sigma = \frac{d}{A * R} \tag{2.11}$$

In order to obtain an accurate measurement of the DC conductivity absorption and capacitive charging currents must be considered [15]. This requires the voltage to be applied for a sufficient duration to allow these currents to dissipate.

Absorption current is a transient current caused by polarization of a dielectric material in a capacitor. The current appears when the dielectric is subjected to an electric field and the dipoles gradually align with the electric field. As the material reaches its new equilibrium, the current decreases. The current can take some time to decay fully to zero. Shorter wait times can be used although it does increase measurement uncertainty [2].

The capacitive charging current charge the electrodes in a capacitor as electrons move from one electrode to the other [2]. It decays rapidly and a shorter wait time as discussed in the previous paragraph would require the charging current to decay to a negligible level. This is because the voltage cannot be measured with desirable accuracy before the charging current has dissipated.

2.4.3 Dielectric breakdown testing

The test measures breakdown voltage, which depends on all the parameters discussed in Section 2.1.4. To relate the measured breakdown voltage to the oil properties, the electric field breakdown strength $\mathbf{E}_{BD}$ is calculated from the test setup geometry using Equation 2.12, where U_{BD} is the breakdown voltage and d is the distance between the electrodes [2]. The electric field is assumed to be uniform at the location of the breakdown.

$$\mathbf{E}_{BD} = \frac{U_{BD}}{d} \tag{2.12}$$

The test cannot provide a universally valid value that is applicable for all operating conditions due to the large number of factors influencing breakdown voltage. Standardized testing methods are therefore applied in order to have some degree of comparability between different types of insulators. However, the large variation that can occur from environmental factors or unintended pollutants introduce uncertainties of up to 30% of the measured value. Since the test also depends on the materials in contact with the oil and the specific geometry used, the measurements that are collected in breakdown voltage tests are only applicable to that specific setup and conditions [2]. However, the measurements between different samples under those test conditions are comparable. Therefore trends related to aging, moisture, or contaminants can still be identified. However, the presence of gas bubbles and contaminants significantly affects the breakdown voltage. Bubbles and decomposition particles that arise as a consequence of previous tests must be removed from the stressed volume after the test. This is accomplished by stirring the oil and then waiting for a minimum of two minutes allow the dissolved gases to dissipate and the particles settle at the bottom. If a longer wait time is used the same time should be applied to all samples for consistent testing conditions.

The voltage rise rate is important as well and should, according to IEC 60156:2025, be kept to 2-3 kV/s as much as possible since this rise rate will affect the breakdown voltage [1, 2]. The most important requirement is to keep it consistent across all tests to ensure consistency between measurements.

3
Test setup

In this chapter the sampling, experimental test setup and age prediction models used for this investigation are presented. The tests were performed in the following order dissipation factor, resistivity and dielectric strength. The order was because DC testing affects the sample more strongly than dissipation factor measurements [16]. Since breakdown events may introduce gas bubbles or soot particles this test was performed last.

3.1 Description of samples

The samples was based on oil from transformers that have been tested as prototypes. The various samples have been in storage for different durations as presented in Table 3.1, where fresh oil was used as a reference sample. The samples were provided by SAAB and the extraction was outside the control of the project. Therefore, it is unknown if there were contaminants left in transformer tanks that were not in the tested oil due to sampling method, since the samples were provided in glass bottles. If that is the case the oil might perform slightly better than in the tank.

Sample	Time in storage (Years)
Fresh	0
2025 Membrane	1
2019 Membrane	7
2018 Membrane	8
2017 Membrane	9
2016 Bellow	10

Table 3.1: Oil samples and their time in storage.

Due to delays during testing of the volume filler alternatives, there was a delay of approximately 1–2 weeks between sample collection and testing. This means that the oil was exposed to nitrogen gas in the storage jars during this period. This is to mitigate any problems that would come from being exposed to air. However, this became known after the testing was finished so there exists a possibility that jars were opened, releasing the nitrogen and replacing it with air. One approach to mitigate gas buildup, regardless of type, would be to degas each sample prior to testing. However, this would introduce a counteracting effect, as it could also remove or alter contaminants introduced during operation or diffused through the membrane during storage. Therefore, it was decided to leave the oil unaltered, since all samples were affected in a similar manner and the objective is to compare differences between them. This must be considered when analyzing the results, as it influences the reliability and interpretation of the measured values.

3.2 Test setup

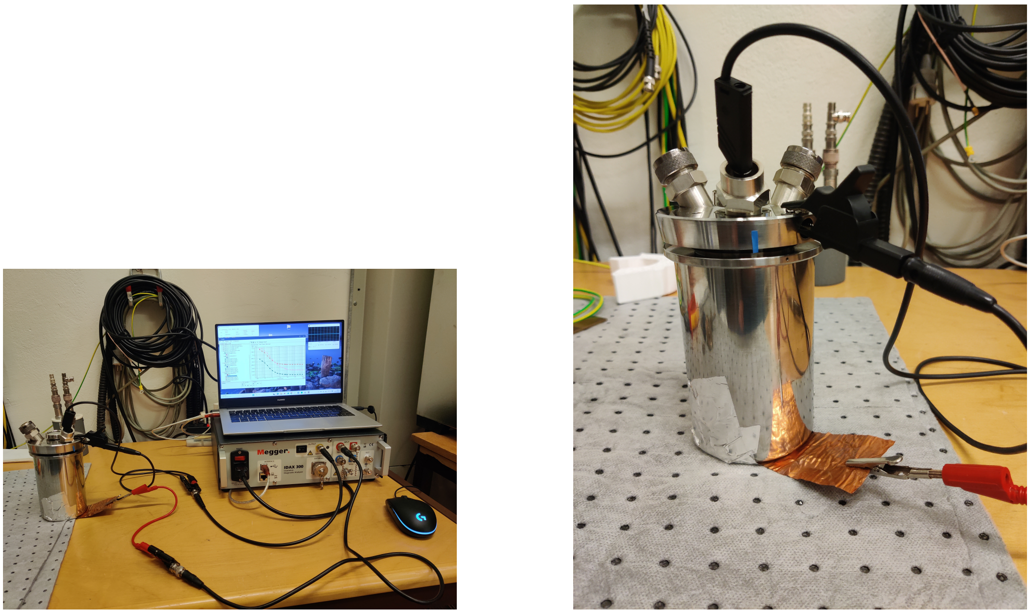
3.2.1 Measuring dissipation factor $\tan(\delta)$, and permittivity

The dissipation factor and complex capacitance measurements were performed in accordance with IEC-60247-2004 with the test cell Tettex 2093a which can be seen in 3.1b. This test cell consists of two concentric cylindrical electrodes 2 mm apart, providing a homogeneous field distribution for testing. The test cell is rated for applied electric fields between 0.03 kV/mm and 1 kV/mm with an empty cell capacitance of 60 pF. The measurements were performed with the IDAX which is connected to both electrodes of the test cell after discharging any residual charge stored in the test cell capacitance, the layout is presented in 3.1a. The outer electrode was energized to 140 V using a frequency sweep in the frequency range 22 mHz - 10 kHz. The inside is connected directly to the measuring device where the measurements are recorded. The IDAX 300 performs this process automatically and the readings of $\tan(\delta)$ and complex capacitance can be then be analyzed. Permittivity can also be calculated from these measurements. To keep the repeatability high the temperature of the container and oil should be maintained at a consistent value for all measurements, in this case the tests performed at room temperature of approximately 20° C. Calibration of the dielectric response measurements and verification of the electrical connections were performed through testing a reference capacitor of 10 pF.

3.2.2 Dielectric strength test

To perform the dielectric breakdown measurements a dielectric strength tester, the ASEA Oil testing set TUPE 60 shown in 3.3a, was used. Initially, the dielectric strength tester was calibrated to improve the accuracy of the voltage measurements. Connections for a digital multimeter were installed on the dielectric strength tester. The multimeter measures the voltage on the low voltage side of the transformer. To determine the transformer ratio a high voltage probe was used to measure the voltage on the high voltage side of the transformer. Several voltage levels were tested, and the transformer ratio was determined using $a = \frac{2V_{peak-HV}}{\sqrt{2}V_{RMS-LV}}$. Where the factor of 2 accounts for the high voltage probe measuring the potential at a single electrode, while the multimeter measures the voltage difference between the two electrodes. Since the electrode voltages are phase shifted by 180°, the resulting peak-to-peak voltage is twice the electrode amplitude. To present the measured voltage in RMS, the peak voltage is converted by dividing with $\sqrt{2}$. Using this method, the transformer ratio of the dielectric strength tester was determined to be 300, meaning the high voltage side is 300 times the low voltage side.

The measurements were performed based on IEC 60156:2025 [17], however due to limitations in sample volume modifications were made. A volume filler was de-



(a) Complete overview of the connected test rig.

(b) Connection setup to Tettex 2093a.

Figure 3.1: Test setup for measuring the dielectric parameters $\tan(\delta)$, ϵ', and ϵ''.

veloped and implemented to solve problems with sample volume considerably lower than specified in the standard. To verify that the modified setup produced comparable results a test with fresh oil was performed, one measurement using the standard test cell and one using the modified configuration including the volume filler. The final modified version was a 3D-printed horseshoe-like shape made out of polypropylene which can be seen in Figure 3.2. The material was chosen as it is chemically inert with the oil at room temperature and suitable for 3D printing. New volume fillers can then be produced for each test, minimizing the risk of contamination.

The test cell consists of a ceramic container with two spherical-cap electrodes with a radius of 25 mm separated by 2.5 mm as per IEC 60156:2025 and can be seen fitted with the volume filler in Figure 3.3b. The test cell was cleaned to remove residue of previous tests and then inserted back into the test rig. The volume filler was not cleaned but a new one was printed for each test. The polypropylene material could deform during oven drying used for moisture removal, while insufficient drying could leave residual moisture trapped inside the structure or on surface ridges, potentially contaminating the oil sample.

Before testing the sample was agitated to evenly distribute contaminants throughout the oil. After agitation the oil was poured into the test cell carefully to minimize the formation of air bubbles in the oil. Prior to energizing the test rig the voltage adjuster was set to 0 V. Voltage was then increased at approximately 3 kV/s and

Figure 3.2: Volume filler made out of polypropylene.

(a) Control panel for the dielectric strength tester.

(b) The container with the volume filler mounted in the dielectric strength tester.

Figure 3.3: Dielectric strength test setup.

the voltage level was monitored continuously. When breakdown occurred a breaker activated and the corresponding voltage was recorded.

This was repeated 10 times where the two highest and two lowest values excluded as outliers and then the average of the remaining values was calculated. Between each test the oil was stirred to distribute any contaminants generated by the breakdown event. Normally, after stirring a waiting period of 1 min between the tests according to IEC 60156:2025. However, with the smaller volume a wait time of 8-10 minutes produced more consistent measurements, therefore this wait time was used in this case. As the breakdowns occurs stochastically the confidence interval is set to 30 % based on the standard IEC 60156:2025 to ensure the probable voltage levels where a breakdown occurs at are covered.

As mentioned in Section 3.1, the oil samples were exposed to nitrogen in the jar for approximately 1–2 weeks prior to testing. The effects of this exposure on dielectric strength was evaluated. The measurements showed a breakdown field strength of 15 kV/mm, compared to 18 kV/mm for oil that was degassed immediately before testing. This corresponds to an approximate 17% reduction. It should be noted, however, that freshly degassed oil is more prone to re-absorption of gases than oil that has already reached some level of saturation before being exposed to air.

The results indicate that the tested samples exhibit slightly lower dielectric strength than they would have shown if analyzed immediately after extraction from the transformer tanks. The comparison suggests that air exposure may reduce measured breakdown field strength, but the magnitude may vary between samples. Therefore, when assessing whether the oil meets safety regulations, it is important to consider that the presented results likely underestimate the true condition of the oil within the transformers.

3.2.3 Method for resistance and conductivity test

To measure the resistivity the same test cell as used for the dielectric breakdown measurements together with the Megger MIT1025/2. The voltage applied was a series of voltage steps with increments of 1 kV applied for 1 minute each and the final value after 1 minute was recorded in order to get the most accurate DC resistance. This was because absorption- and capacitive charging current have sufficient time to decay.

This method demonstrates how resistance differs as a function of applied voltage. The presence of moisture and pollutant particles will show a decrease in resistance when voltage increases. For solid insulation systems a decrease in measured insulation resistance in the order of megaohms when the voltage changes should be taken as a sign of weakness in the insulation [18]. This method cannot show a definite reason for the weakness but it can show the necessity for further investigation.

Similar to the test for dissipation factor only one test were performed. During cleaning, the test cell was not rinsed with the sample oil. This was implemented to conserve the limited sample volume.

3.3 Modeling aging behavior

To analyze performance degradation and lifetime expectancy for the insulation oil, aging models were developed based on the experimental data. The models explored include common curve-fitting tools such as linear, polynomial, logarithmic, and exponential. To evaluate model fit, the coefficient of determination R^2 was used to compare the models to the datasets. Furthermore, a physical interpretation was performed to eliminate physically unrealistic predictions.

4
Results

This chapter presents and breaks down the results from the experimental results as well as the age prediction models.

4.1 Dissipation factor, $\tan(\delta)$ test

The result shown in Figure 4.1 shows there is a difference between the fresh oil and the aged samples. There is a close grouping of the samples from 7, 8 and 9 years with the 1-year sample showing a slightly higher dissipation factor. The sample from 10 years ago follow the fresh sample closely indicating relatively minor aging effects in that sample.

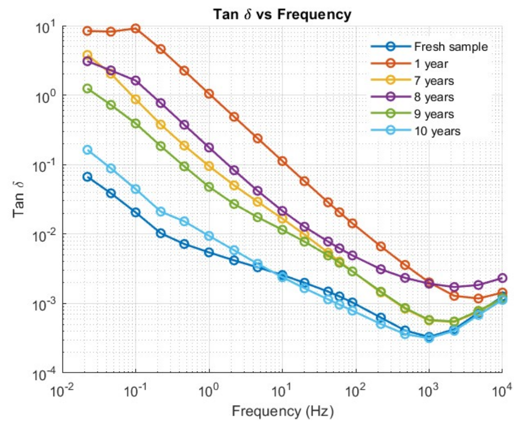
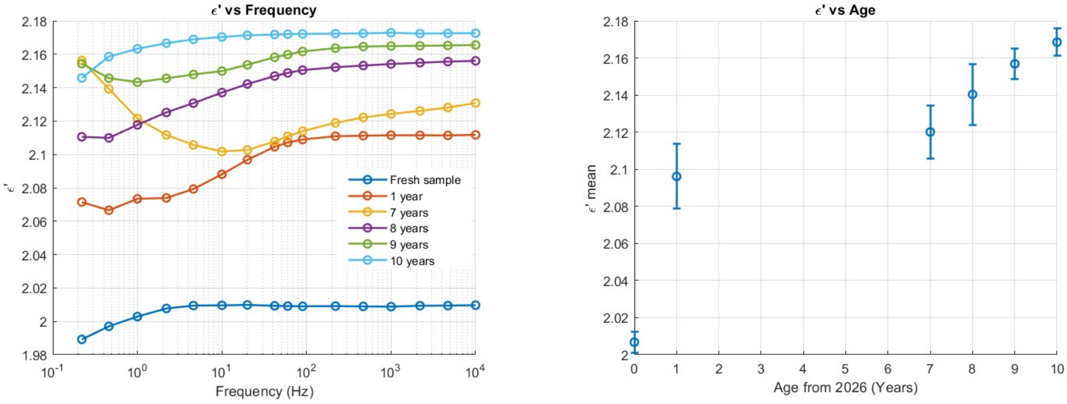


Figure 4.1: $\tan(\delta)$ over a frequency sweep.

4.2 Permittivity test

Figure 4.2a shows the real permittivity as function of frequency for the test samples. An increase in permittivity with increasing aging time especially in the higher frequency range. The fresh sample saturates around $\epsilon_r' = 2.01$ where the aged samples reached values ranging between 2.1-2.17 with increasing values observed for older samples.

In Figure 4.2b the average values for each sample were plotted to facilitate comparison between the samples. The confindence interval represents the standard deviation from the measured values in the frequency sweep. In average the real permittivity increased of roughly 5% between the fresh sample and the sample aged one year. The following samples show a continuous increase with the aging time.



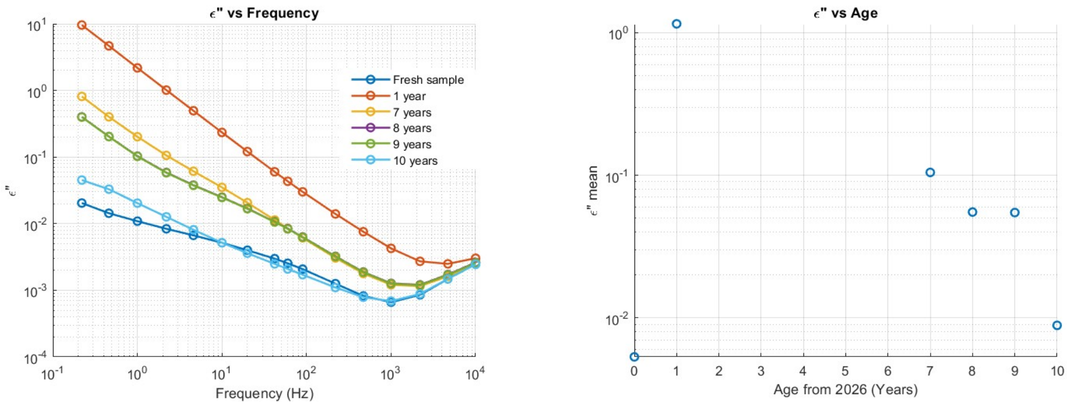
(a) Real permittivity over a frequency sweep.

(b) Averaged values for each sample.

Figure 4.2: Real permittivity measurement results.

The imaginary part of the permittivity is shown in Figure 4.3 where Figure 4.3a presents the frequency dependence and Figure 4.3b shows the average values. Regarding the frequency dependence for ϵ'', greater variation in dielectric losses between the samples is observed at lower frequencies where the fresh sample and 10-year-old bellow-sealed sample exhibit the lowest dielectric losses. As the frequency increases, the responses converge. However, minor differences remain between samples.

From the averaged values, the samples can be grouped according to their dielectric loss behavior. As mentioned previously the 10-year-old sample showed similar behavior as the fresh sample, the 7-, 8-, and 9-year-old samples performed similarly and the 1-year-old sample demonstrated significantly higher dielectric losses.



(a) Imaginary permittivity over a frequency sweep.

(b) Averaged values for each sample.

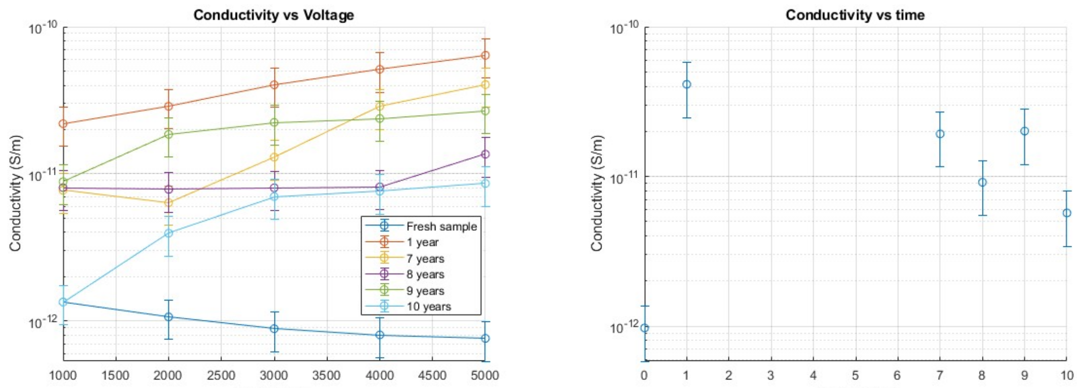
Figure 4.3: Imaginary permittivity results.

4.3 Resistance and conductivity test

From the resistance sweep measurements the DC resistivity for the test geometry was measured and is presented in Table 4.1. After applying the geometric correction factor, the conductivity at each voltage level is shown in Figure 4.4a. To facilitate comparison between samples, the average conductivity of each sample can be seen in Figure 4.4b. As an overall trend the aged samples exhibit increasing conductivity with increasing voltage. The fresh oil is the only sample that show a decrease in conductivity with increasing voltage, although the change is minor. Regarding the averaged values, the results are quite similar to ϵ'', where the 1-year-old sample showed the highest conductivity and the others showed relatively similarly conductivity without any clear dependence on aging time.

	Resistance at different voltage levels				
Age	1000 V	2000 V	3000 V	4000 V	5000 V
Fresh oil	$1.184T\Omega$	$1.493T\Omega$	$1.796T\Omega$	$1.979T\Omega$	$2.09T\Omega$
1 year	$72.6G\Omega$	$55.3G\Omega$	$39.5G\Omega$	$31.0G\Omega$	$24.9G\Omega$
7 years	$206G\Omega$	$250G\Omega$	$122.5G\Omega$	$55.4G\Omega$	$39.6G\Omega$
8 years	$197.5G\Omega$	$203G\Omega$	$198.1G\Omega$	$195.3G\Omega$	$117.1G\Omega$
9 years	$180G\Omega$	$85.8G\Omega$	$71.1G\Omega$	$66.9G\Omega$	$59.4G\Omega$
10 years	$1.182T\Omega$	$403G\Omega$	$227G\Omega$	$209G\Omega$	$185.4G\Omega$

Table 4.1: Resistance measurements for different voltage levels.



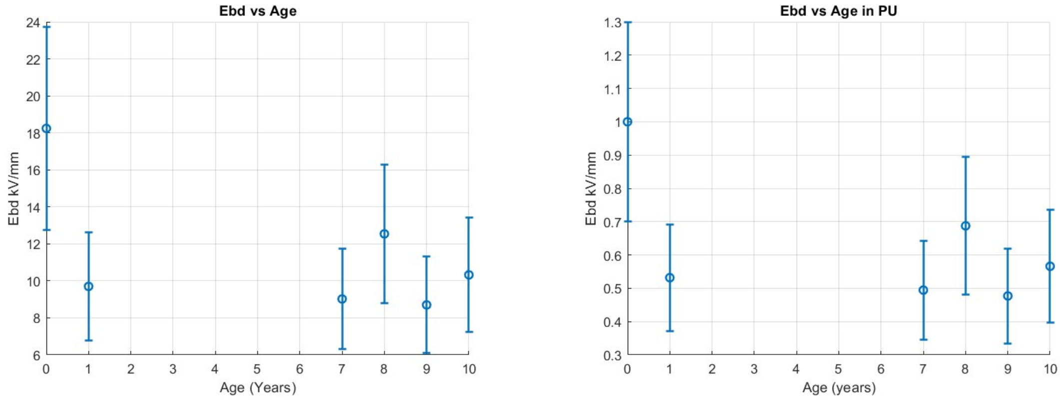
(a) Conductivity at different voltage levels.

(b) Average conductivity for differently aged samples.

Figure 4.4: Conductivity results.

4.4 Dielectric strength test

From the dielectric strength tests performed, the average breakdown voltage is shown in Figure 4.5a. Similarly, a corresponding normalized plot was generated where all values were normalized against the fresh sample in Figure 4.5b. The results showed that breakdown occurs at an electric field strength of 18 kV/mm for the fresh sample. With the aged samples the average breakdown occurs at between 47-68% of the electric field strength of the fresh sample.



(a) Breakdown voltages for different sample ages.

(b) Breakdown voltages normalized to fresh sample.

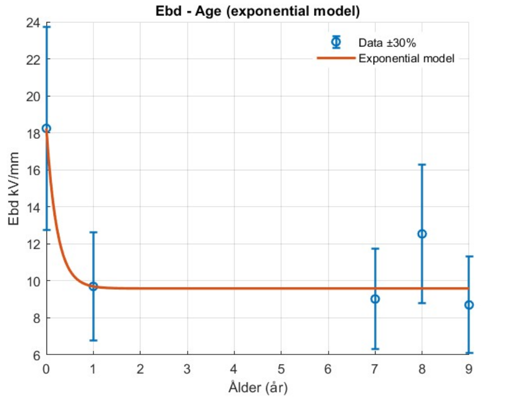
Figure 4.5: Electrical breakdown results.

4.5 Aging models membrane sealed containers

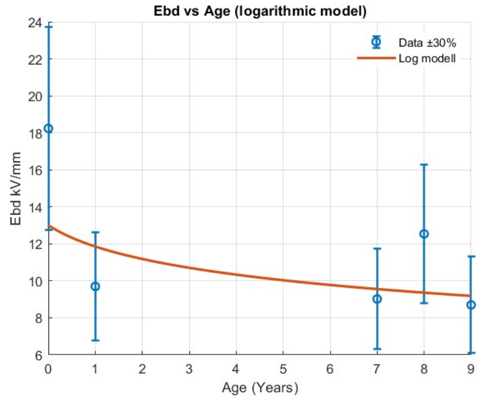
To estimate the lifetime the results from the tests curve-fitted models are shown in Figures 4.6 and 4.7. These models that best describe the aging behavior over time. Furthermore, the R^2 values are presented in Table 4.2 where the R^2 value for the ϵ'' model is presented. However, the model deviated too much and was considered physically unrealistic and was therefore excluded from further analysis. Lastly, an estimation based on a given safety criteria of 5 kV/mm for breakdown field strength showed a life expectancy of 123 years when using the logarithmic model. As this estimate significantly exceeds the recommended storage time for transformer oil, it is not considered a reliable representation of the actual degradation process.

Aging model	R^2
Ebd exponential, 4.6a	0.7495
Ebd logarithmic, 4.6b	0.2725
ϵ' logarithmic, 4.7a	0.9681
ϵ' linear, 4.7b	0.9398
ϵ'' logarithmic, not shown	0.1460

Table 4.2: R^2 values for aging models.

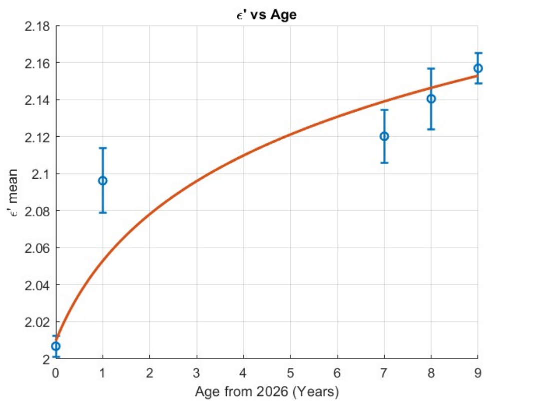


(a) Exponential model for dielectric strength.

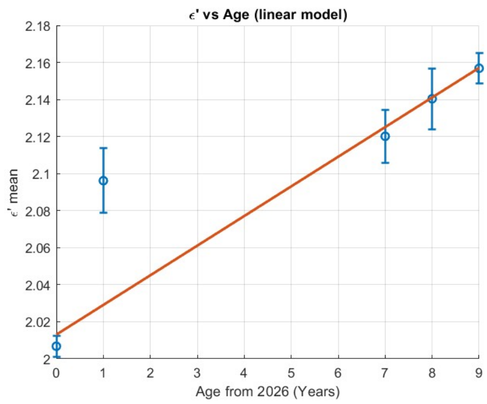


(b) Logarithmic model for dielectric strength.

Figure 4.6: Aging models for dielectric strength.



(a) Logarithmic model for real permittivity.



(b) Linear model for real permittivity.

Figure 4.7: Aging models for real permittivity.

5
Discussion

This chapter discuss the test results and cross reference the performance with already done studies from a literary study to find potential reasons behind the performance results.

5.1 Analysis of $\tan(\delta)$ measurements

As shown in Section 4.1, the results indicate that the aging effects influencing $\tan(\delta)$ may be more strongly associated with factors other than storage time. The group of the samples aged 7-9 years indicates some measurable aging. However, the sample from 2025 has exhibited a greater deterioration than the older samples despite shorter storage duration. This suggests that aging is not primarily correlated with storage duration, but rather with the operational time of the transformer. Regarding the 10-year-old sample, the absence of deviation from the fresh sample may indicate that the membrane seal plays a major role in the aging process. This tank model does not utilize a membrane seal. Instead, the tank is fully sealed and utilizes bellows mechanism to accommodate minor pressure variations. This bellows has been shown to not let gas diffuse through during pressure tests. An alternative explanation may be that this unit has undergone fewer operational tests than the other samples, resulting in minimal observable aging in this parameter. If operational testing is assumed to be a major contributor to changes in $\tan(\delta)$, the results may suggest a correlation between membrane-sealed transformers and increased dielectric deterioration. This interpretation is further supported by the insulation oil's reaction to rubber [19]. However, due to the limited sample size, these observations cannot be considered conclusive, although they may indicate a potential correlation. To have a more definitive result more samples would be needed with a more defined history or possibly more controlled aging by isolating a number of factors. Since the transformers were not initially tested for contaminants, conducting such analyses after the breakdown tests would provide limited value, as the breakdown process itself introduces particles into the oil. Therefore, new samples would need to be collected and analyzed for contaminants prior to breakdown testing. However, since the results of this study indicate limited aging effects associated with storage time, samples obtained immediately after initial product testing could provide valuable information regarding the presence of detrimental contaminants.

Comparison of the $\tan(\delta)$ results with the real and imaginary permittivity indicates that deviations in the imaginary permittivity dominate the frequency-dependent behavior. This is consistent with the relatively constant behavior of the real permittivity across the applied frequency range. Furthermore, the results suggest that dielectric losses decrease at higher frequencies due to the reduced influence of conductive mechanisms within the system.

5.2 Evaluation of Permittivity measurements

For the real permittivity, the variation between the samples was smaller, with increases in permittivity of up to 9%. Although the aged samples exhibit only a minor decrease in performance, the increase in permittivity may indicate the introduction of polarizable contaminants, contributing to a more capacitive insulating material. Since both an initial increase during the first year and a gradual long-term increase were observed, one possible explanation is that contaminants are introduced both during operational testing and gradually over storage time.

For the aging model of the real permittivity, both the linear and logarithmic models provide similar fits with regard to the R^2 value. The logarithmic model may be more suitable when considering the rapid initial increase, which could indicate accelerated aging during prototype testing. However, the linear model may provide a better representation if the 1-year-old sample is considered an outlier, as its deviation from the overall trend may disproportionately influence the logarithmic fit. In both cases, the system exhibits continuous degradation over time, which is consistent with a gradual introduction of contaminants through the membrane or chemical interactions between the oil and container materials.

Since the imaginary permittivity is related to frequency-dependent system losses, as described in the latter part of Equation 2.8, the approximately linear decrease observed at lower frequencies in Figure 4.3a is expected. At higher tested frequencies, the sample responses converge and either flatten or increase slightly, which may indicate a growing contribution from polarization losses. This overall behavior is expected, since conductive effects associated with DC behavior become more pronounced at lower frequencies. As the sample values differ less at higher frequencies, this may indicate that the introduced charge carriers primarily contribute to low-frequency conductive behavior. Furthermore, ϵ'' may also be related to the DC conductivity, since the averaged values exhibit similar trends over time.

One reason for the degradation may be the impact from the voltage level used in the testing, as higher voltage levels seem to accelerate the aging [20]. Additionally, operational duration may contribute to degradation in a similar manner. The latter factor, combined with the limited historical information available for the samples, may explain the non-linear degradation behavior observed in the data.

The aging models evaluated for ϵ'' did not provide a satisfactory fit to the data, yielding an R^2 value of only 0.1460, which indicates poor agreement with the measured data points. This may be due to the substantial variation between the measured values, particularly the pronounced deviation of the 1-year-old sample. Furthermore, the limited number of samples increases the influence of each individual data point on the resulting model.

5.3 Interpretation of conductivity measurements

The conductivity is shown in Table 4.1 and Figure 4.4a to be dependent on the voltage. However, in the fresh sample, the variation was small and the conductivity decreases with increasing voltage. In contrast, the aged samples exhibit larger variations and increasing conductivity with increasing voltage. The increased conductivity suggests the presence of contaminants, particularly since the conductivity increases with increasing voltage [21]. One possible explanation is moisture content in the oil or contaminant particles that contribute to field enhancement between the electrodes. At 1 kV the membrane-sealed tanks show a higher conductivity indicating an increased concentration of charge carriers with a weaker dependence on the electric field. As the voltage increases, most of the samples become more conductive. However, the 10-year-old bellows-sealed sample shows a pronounced early increase. One reason for this may be the presence of contaminant particles that become ionized at higher field strengths thus increasing the amount of free charge carriers. Since this trend was observed in all aged samples, it may indicate that similar contaminants are present in most of the oils.

When the average conductivity is considered with respect to aging time, the results suggest that aging occurs primarily during product testing. If that is the case, the difference between each sample could depend on the duration of electrical testing.

As mentioned in Section 5.2, similarities can be observed between the results for σ and ϵ''. Since the measurements are based on similar dielectric response mechanisms, this correspondence appears reasonable. The primary differences between the tests were the applied voltage levels, measurement geometry, and frequency range, where the conductivity measurement was performed under DC conditions. Therefore, the low-frequency behavior of ϵ'' is expected to correspond most closely to the conductivity measurements. Comparing the two sets of results further supports the hypothesis that aging introduces contaminants which primarily increase the DC conductivity of the oil.

5.4 Assessment of dielectric strength measurements

The dielectric strength test provided the strongest indication that there was significant aging associated with the quality testing procedure. This interpretation is based on the substantial drop in E_{bd} between the fresh and 1-year-old sample. The rest of the values were relatively consistent which would indicate that the aging as a result of diffusion through the membrane was limited over the investigated timespan. Since the time dependent aging does not seem to be substantial it provides further indication that there is an early factor contributing to this reduction in E_{bd}.

Possible factors can be aging due to the electrical testing, contaminants in tank before filling, or oil reacting chemically with other materials and that reaction occurs mostly in the beginning or a combination of both.

One possible explanation for the reduced breakdown voltage in the aged samples is the presence of solid particles such as dust or debris originating from the solid insulation. An increased concentration of conductive particles in the insulation oil lowers the voltage at which breakdown occurs [22]. Furthermore, non-conductive particles also show a correlation with contamination and reduced breakdown voltage [23]. When comparing with conductivity measurements, a similar trend can be observed where decreased conductivity corresponds to higher breakdown voltage.

Like all other tests, the limited sample size introduced uncertainty here as well. If the reduction in breakdown voltage is primarily caused by electrical testing and operational exposure rather than storage time, then the results would indicate limited aging during storage, which would be a positive indication for long-term reliability since the transformer spends the vast majority of its lifetime unenergized. However, further testing with a larger sample size would be required to draw definitive conclusions.

The aging models for the breakdown field strength produced physically reasonable trends based on the measured values. The exponential model had a higher R^2, which indicates a better fit to the measured data points. It also showed a rapid initial decrease, which corresponds to the hypothesis of rapid degradation following the initial electrical testing. The issue with the exponential model is that it approaches a constant value over time. At that point, the model predicts no further significant degradation with increasing aging time. Since the system does not provide ideal storage conditions, the oil is expected to undergo continuous degradation, which limits the physical realism of the exponential model. This limitation is partly addressed by the logarithmic model, which predicts a continuous gradual decrease over time. However, the logarithmic model shows larger deviations from the measured data and does not accurately represent the initial data point. As part of the study, an estimated lifetime was derived from the logarithmic model. The resulting estimate of 123 years should be considered highly optimistic, which highlights a limitation of purely mathematical extrapolation. Furthermore, this estimate only applies to geometries similar to the test setup, since the electric field distribution is strongly dependent on electrode geometry. For other configurations, the critical field strength may be reached at lower applied voltages.

5.5 Discussing possible aging factors

Based on the correlations observed in these tests, the literature review suggests several possible mechanisms behind the observed aging behavior, assuming that the results are representative of sample age and that measurement errors are limited.

The first possible aging factor is the electrical testing performed under operating voltage conditions. The applied voltage waveform consists of fast square-wave pulses. Signals containing high-frequency components have been linked in the literature to increased levels of PDs in oil-insulated systems [24]. Since the signal used during prototype testing has short rise times, it follows the trend reported in [7], where shorter rise times are associated with increased electrical stress and higher PD activity. The increased electrical stress associated with PD activity may accelerate degradation of the complete insulation system, thereby increasing the release of degradation by-products into the oil. Furthermore, the presence of PD activity has been confirmed through SAAB's internal testing of the complete insulation system. Partial discharges are known to accelerate insulation aging through localized heating and chemical degradation. The energy released during PD activity can initiate reactions in both the oil and surrounding insulation materials. One example of such a material is the polyimide insulation used in the transformer windings. When exposed to PD activity, polyimide materials have been shown to produce decomposition products such as water vapor, carbon monoxide, and hydrogen gas [25]. Moisture is one of the most critical contaminants affecting transformer oil since a small amount of water in oil has a large effect on the insulation strength, conductivity and $\tan(\delta)$ in the oil [2, 21]. This may explain the pronounced initial aging observed in the results, where even the 1-year-old sample showed clear signs of degradation. The conductivity measurements also showed increasing conductivity with increasing voltage, which may indicate the presence of moisture or ionized contaminants in the insulation oil. This behavior could partially be explained by extensive PD activity during the initial testing phase. However, the $\tan(\delta)$ measurements show that the 2016 sample exhibits minimal aging in dielectric losses, suggesting that PD-related degradation alone cannot fully explain the observed behavior.

Another potential aging mechanism is related to the membrane seal. As discussed above the sample from 2016 showed limited aging in the $\tan(\delta)$ tests. The biggest difference between these samples is that the transformer tank from this sample does not feature the membrane seal. This may indicate that the membrane seal affects dielectric losses more strongly than the other measured parameters. Diffusion of helium gas has been observed in internal tests performed by SAAB and in a study by Zhang [12] the speed of diffusion though flourosilicone is done and the speed of diffusion of different gasses is discussed. The study showed that not only hydrogen gas can diffuse and the inclusion of these gas bubbles could be a reason for the difference in the age of the oil. However, since the exact history of the samples is not exactly known there are uncertainties as to the temperature and pressure that they have been exposed to both during testing and in storage. This would influence the diffusion of particles through the membrane. Gasses introduced through the membrane will affect the capacitance of the oil, something that can be seen in the $\tan(\delta)$ test and if that would be a dominant aging factor that could explain the way that the graph looks. The effects of membrane diffusion cannot be directly confirmed in this study, since oil extraction and dielectric breakdown testing introduce gases into the oil independently. However, further experiments designed to isolate membrane diffusion as an aging factor could provide additional clarification.

5.6 Reliability of measurements

One major concern regarding measurement reliability is the limited sample size. This means that values which might be identified as outliers in a larger dataset must here be treated as representative measurements. For example, the 2025 sample showed significantly different behavior compared to the other samples, particularly in the $\tan(\delta)$ measurements. This could be due to differences in testing history, manufacturing defects, storage conditions, or the possibility that the sample represents a statistical outlier. None of these explanations can be confirmed, since the operational history of each transformer tank was not fully documented. Therefore, any attempt to fully explain this deviation would remain speculative. However, since the result was obtained experimentally, it is treated as representative of a transformer unit of that age in the absence of evidence suggesting otherwise.

The absence of chemical analysis makes it difficult to determine the exact mechanisms responsible for aging. Chemical analysis was outside the scope of this study, which primarily focused on electrical insulation parameters. However, this limitation prevents definitive identification of the dominant mechanisms responsible for oil degradation. This uncertainty is also reflected in the aging models. Since the underlying degradation mechanisms cannot be conclusively identified, they cannot be incorporated directly into the aging models. Consequently, the aging models should be interpreted with significant uncertainty. This uncertainty is further increased by the limited sample size. The clearest conclusion that can be drawn from this thesis is that measurable aging is present, and that the differences between the samples suggest that the membrane seal may contribute to degradation in some of the investigated parameters.

6
Conclusion

In this thesis, measurements were collected from transformer oil samples originating from transformer tanks of different ages. These transformers used membrane seals to accommodate pressure variations. Previous testing had shown that the membrane seal allowed gas diffusion into the transformer tank. The question arose if this would affect the aging parameters of the transformer oil. Measurements of $\tan(\delta)$, permittivity, conductance and dielectric strength were performed on the oil samples.

The results indicate differences between the membrane-sealed transformers and the bellows-sealed transformer of similar age, particularly in the $\tan(\delta)$ measurements. However, these differences were not observed in the measurements for conductivity or dielectric strength. All aged samples nevertheless exhibited measurable signs of degradation across the investigated parameters.

Several possible degradation mechanisms were discussed based on the experimental results and literature review. One proposed mechanism was diffusion of gases and moisture through the membrane seal, which appeared to influence primarily the $\tan(\delta)$ measurements. This interpretation is supported by the larger difference observed between the membrane-sealed and bellows-sealed transformer tanks for this parameter. Another proposed aging factor was the electrical stress applied during quality testing. This interpretation is supported by the sharp reduction observed in both dielectric strength and conductivity measurements between the fresh and aged samples. This could indicate that the quality testing was a significant contributor to the drop in dielectric strength. Another possible contributing factor is the presence of moisture or contaminant particles within the oil. These contaminants could also explain the observed increase in conductivity and reduction in dielectric strength, while additionally contributing to increased dielectric losses.

In conclusion, no single definitive aging mechanism could be identified. Further testing would therefore be required to determine the extent to which each proposed mechanism contributes to oil degradation. However, the measurements indicate several possible degradation mechanisms that warrant further investigation in order to better understand the long-term deterioration of the oil. The results also suggest that the membrane-sealed design may contribute to some aspects of the observed aging behavior.

7
Future work

This thesis has demonstrated that further investigation of aging mechanisms in membrane-sealed transformer tanks is feasible. For future studies directly related to the transformer tanks investigated in this work, or similar ones, one possible approach would be controlled artificial aging experiments where individual parameters are isolated. For example, transformers could be exposed to the operational voltage waveform for different durations in order to isolate the effect of quality assurance testing. This would help determine whether the rapid initial degradation observed in several measurements is primarily caused by electrical testing or by another mechanism.

Another parameter of interest is the extent of gas diffusion through the membrane under different environmental conditions. This could be investigated using dissolved gas analysis of transformer oil exposed to different pressures over varying exposure durations. Such measurements would help quantify the concentration of dissolved gases within the oil. If these samples were subsequently subjected to dielectric measurements, the influence of dissolved gases on insulation performance could be evaluated more directly. This type of investigation was outside the scope of the present work but could provide valuable insight into the degradation mechanisms. The same can also be said for a moisture analysis of the oil.

Studying the investigated parameters under operational voltage conditions would also be of significant interest. The equipment used in this work could neither generate the operational waveform nor accurately and safely measure dielectric properties under such conditions. Therefore, reproducing the operational waveform during dielectric testing could provide more accurate measurements of oil performance within the operationally relevant frequency range. As shown in previous studies, high-frequency pulsed voltage waveforms can significantly influence dielectric breakdown behavior [26].

Future studies should aim for a larger sample size in order to improve statistical reliability and develop more accurate aging models. Such models could provide more reliable estimates of transformer oil lifetime. If a larger sample size is not possible to achieve isolation of parameters become more important as to give a more detailed explanation of the aging factors.

Another possible direction for future work is investigating broader applications of membrane-sealed transformer tanks beyond the specific implementation. Such studies could evaluate whether different operating conditions influence aging behavior sufficiently to justify alternative transformer designs. Although this type of design is likely applicable only in specialized cases, further studies could help identify situations where membrane-sealed solutions provide advantages over conventional transformer designs.

Although several of these topics have been addressed in the literature, many of the investigated parameters depend strongly on the specific transformer geometry and operating conditions. Therefore, the proposed future studies would still be valuable for the specific transformer design investigated in this work.

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