Doctoral Thesis

Measurement and analysis of dielectric response in oil-paper insulation systems

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MEASUREMENT AND ANALYSIS OF DIELECTRIC RESPONSE IN OIL-PAPER INSULATION SYSTEMS

A dissertation submitted to the
SWISS FEDERAL INSTITUTE OF TECHNOLOGY ZURICH

for the degree of
Doctor of Technical Sciences

presented by
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Abstract

The measurement of dielectric response of oil-paper insulation systems in the time or frequency domain provides novel diagnostic methods for quality control of medium and high voltage power transformers. If the insulation system is linear, the information obtained in both domains is equivalent. Furthermore, the system can be described with classic relations of linear dielectric response theory.

The aim of this work is to measure and to analyse the dielectric response of oil-paper insulation systems in dependence upon material quality, moisture content and ageing products in oil and pressboard, geometrical layout and temperature, and also to determine the validity limits of linear dielectric response theory. The final goal of this project is to propose a reliable diagnostic method, based on measurement of relaxation currents, for the assessment of the quality of oil-paper insulation in transformers, particularly the moisture content and ageing state of its solid component, i.e. the pressboard.

To attain this goal, the dielectric properties of well defined test objects were quantified in the time domain by means of the relaxation (polarization and depolarization) currents, recovery voltage and the "polarization spectrum"; this involves a special procedure of recovery voltage measurement. In the frequency domain, this quantification is carried out with complex capacitance and tan\(\delta\), determined over a wide frequency range.

The investigations are performed on homogenous test materials, new and artificially aged impregnated pressboard and mineral oil samples with different moisture contents, on multi-layer arrangements, consisting of a series arrangement of oil ducts and pressboard disks with varying volume ratios, a configuration representative of the main insulation of power transformers. Finally, tests were also performed on several new and used power transformers.

The results of these investigations demonstrate that any oil-paper insulation system can be adequately described by means of the basic relations of linear dielectric response theory. A simple equivalent circuit determined from measured relaxation currents can be used to calculate all other dielectric responses in the time or frequency domain.

Systematic investigations on multi-layer samples clearly show that the total dielectric response of such test objects depends on the dielectric response of single constituent materials, oil and impregnated pressboard and their volume ratio.

It is also shown that the relaxation currents (dielectric response in general) of a power transformer can be calculated from an "extended" equivalent circuit or from the corresponding relations of linear dielectric response theory, if the geometric layout of the main insulation and the dielectric properties of its
constituent materials are taken into account. Further, it is also demonstrated that it is possible to make quantitative statements about the moisture content and ageing condition of pressboard used in power transformers, if the dielectric properties of the pressboard in dependence upon moisture content and/or ageing products are known.

Concerning the method used for quantification of dielectric response, the measurement of relaxation currents is an appropriate and easy-to-apply method for detecting the change of dielectric properties in oil-paper insulation systems. The measurement of relaxation currents is particularly adequate for investigation of laboratory samples with small capacitances. Contrary to other dielectric responses like recovery voltage or derived "polarization spectrum", the interpretation of relaxation currents is more fundamental due to the fact that the basic dielectric quantities such as DC conductivity and dielectric response function are in a clear relationship to these currents.

Today, the power utilities and transformer manufacturers have a real need to apply reliable on-site diagnostic methods for assessing the condition and thereby also the quality of the power transformers. Their common aim is to minimize the risks of failures and unexpected power outage, which in general may cause significant financial losses. The present experience on relaxation current measurements on over 40 new and used power transformers in the test laboratory of the manufacturer and under on-site conditions within indoor and outdoor stations of power utilities has demonstrated that these currents can also be recorded well on large test objects under "realistic" conditions. Considering that other quantities in the time domain like recovery voltage and "polarization spectrum" or, in the frequency domain, specific quantities, like complex capacitance and tanδ can easily be calculated from relaxation currents, this kind of measurement technique is an appropriate tool for on-site diagnosis of power transformers.
Weiterhin wurde gezeigt, dass die Relaxationsströme eines Leistungstransformators und dessen dielektrische Antwort im allgemeinen aus einer erweiterten Ersatzschaltung oder aus spezifisch abgewandelten Gleichungen aus der Theorie des linearen Dielektrikums berechnet werden können, wenn die geometrische Anordnung der Hauptisolation und die dielektrischen Eigenschaften der enthaltenen Materialien in Betracht gezogen werden. Damit wird gezeigt, dass es möglich ist, quantitative Aussagen über Feuchtigkeitsgehalt oder Alterungszustand des benutzten Pressboards in Leistungstransformatoren zu machen, wenn die Eigenschaften des Pressboards in Abhängigkeit von Feuchtigkeitsgehalt und / oder Alterungsprodukten bekannt sind.


1 Introduction

1.1 Background

In recent years, additional methods to assess insulation systems have been promoted complementary to the classical insulation resistance, power frequency dissipation factor and polarization index measurements. The promotion of these additional methods, which are based on wide range time or frequency measurement of dielectric responses, e.g. relaxation currents, recovery voltage or complex capacitance (dielectric spectrum), is undoubtedly caused by the efforts to add new diagnostic tools for the estimation of insulation quality and for surveillance of new and aged high voltage equipment in power generation and transmission systems, e.g. generators, power- and instruments transformers and cables. The application of such wide range measurements on power transformers has quite recently been triggered by the proposal of Hungarian scientists [Bognar et al., 1990] to sense recovery voltages using a special procedure, from which a so called "polarization spectrum" can be derived and which may be used to quantify the moisture content and ageing of pressboard applied within transformers.

The verification of this assertion, concerning the quantification of pressboard moisture content in power transformers by means of an evaluation of the "polarization spectrum", was one of the motivations to start this work. Another motivation was to extend the on-site application of the relaxation current measurement technique, till then successfully used for integral detection of water trees in polyethylene cables (see ETHZ Ph. D. dissertation of Th. Heizmann, 1994 and [Heizmann, Zaengl, 1993]), for insulation diagnostics of power transformers.

This project was started in 1993 on recommendation of Prof. Dr. W. Zaengl, at High Voltage Laboratory of the Swiss Federal Institute of Technology Zurich (ETHZ), and carried out in collaboration with Swiss power utilities, ABB Sécheron SA, Geneva, FKH "Fachkommission für Hochspannungsfragen", Zurich, Haeffely Trench AG, Tettex Instruments Division, Dietikon and H. Weidmann AG, Rapperswil.

1.2 Objectives and organization of this project

The first objective of this work was to increase the knowledge related to dielectric response of oil-paper insulation systems, by means of measurement of different quantities in the time and frequency domain and their analysis with linear dielectric response theory. The methods to quantify the dielectric response in the time domain are: measurement of relaxation (polarization and depolarization) currents, measurement of recovery voltage and its derived
quantity, the so-called "polarization spectrum". In the frequency domain the quantification of dielectric response was performed by measurements of the complex capacitance and its derived quantity, the dissipation factor tanδ over a wide frequency range (dielectric spectroscopy).

Laboratory investigations were carried out on macroscopically homogeneous samples of oil-impregnated pressboard or mineral oil, but also on multi-layer arrangements of pressboard disks in series with oil ducts. The measurements were carried out in dependence on various parameters, such as moisture content and ageing products in pressboard and mineral oil, geometrical layout (volume ratio oil to pressboard) and temperature.

The final aim of this work was to propose a simple and reliable tool for on-site diagnosis of power transformers, based on measurement of relaxation currents and their evaluation with linear models.

To attain this final objective, it was also necessary to perform additional measurements on power transformers and to determine the applicability limits of the proposed linear models. These investigations have been done on more than 40 new and used units in a manufacturer's laboratory (ABB Sécheron SA, Geneva) as well as on-site in power stations of Swiss power utilities.

In this dissertation, a selection of representative results of the investigations and its fundamentals are presented in the following order:

Chapter 2 provides an overview of dielectric diagnostic methods as applied to transformers, where different conventional and unconventional methods for assessment of insulation quality are discussed.

Chapter 3 lists the basic relations of linear dielectric theory and groups the definition of measured quantities in the time or frequency domain. In this chapter the linear models are also introduced, represented by means of equivalent circuits and described by the corresponding linear relations.

A detailed description of samples investigated and their preparation procedures is presented in chapter 4. Specifications concerning instrumentation used, test set-ups and measurements performed are given in chapters 5 and 6.

In Chapter 7 the results of experiments are presented and discussed in the following order: impregnated pressboard, mineral oil, multi-layer samples and power transformers. In addition, examples for the application of linear models are given for each kind of these samples.

Finally, the main issues of this dissertation are summarized in chapter 8.
2 An overview of dielectric diagnostic methods for power transformers

Power transformers are among the most expensive and strategically most important components of power generation and transmission systems. Their reliability is crucial for the availability of these systems and thus for the quality of power delivery. A failure within a power transformer due to insulation breakdown can generate massive financial losses due to power outage and consequent damages.

Taking into consideration that a major part of the large power transformers, which have been installed in the middle to late 60's in European countries, are still in service, a real need arises for utilities and transformer manufacturers to develop and apply better diagnostic methods for assessing the insulation condition of these power transformers, with the aim to minimize the risks of failures and unexpected power outages [Boisdon et al., 1992; Jarman et al., 1998; Kachler et al., 1998].

2.1 Diagnostic methods

Since early this century, pressboard (cellulose) in mineral oil has been used as standard transformer insulation and has been and still is proven to have suitable electrical, chemical and physical properties. However, with time the oil-paper insulation degrades, especially at higher temperatures and in presence of oxygen and moisture (thermal ageing). The decomposition of paper is accelerated in the presence of moisture and additionally amplified due to the cumulative effect, since it also produces water as by-product. Electrical and mechanical ageing are additional processes which degrade the quality of insulation, caused by different kinds of partial discharges (ionization processes) and vibration. In real operating conditions, these processes act simultaneously, contributing to a total ageing, which affects electrical, chemical and mechanical properties of the whole insulation system [Sillars, 1973; Moser, 1979; Moser, Dahinden, 1987; Fournié, 1990].

In oil-paper insulation, the qualities of the single components, oil and pressboard, are interlinked: a quality change or deterioration of one component inevitably affects the quality of the other one. Therefore, analysis of oil samples taken from power transformers are important for quality estimation of the whole insulation system inclusive pressboard material.

The dominant diagnostic methods used for assessing the insulation condition of power transformers can be divided into two main groups. The first group includes all methods which have been elaborated for physico-chemical and chromatographic analysis of oil samples taken from transformers. In the second
group the diagnostic methods are collected, which are applied on whole oil-paper insulation systems. These "component" test methods, which are in the majority electrical tests of non-destructive character, are directly applied on the terminals of the power transformers.

Available are also methods for direct condition assessment of pressboard material. The most important ones are: the determination of pressboard moisture content by a Karl Fischer equipment with different water extraction techniques [Scholz, 1984; IEC 60814, 1997], and the determination of degree of polymerization (DP-value) [IEC 60450, 1974]. The DP-value, indicating the decomposition degree of cellulose chains due to thermal ageing, is a reliable method for assessing the degradation of pressboard [Shroff, Stanett, 1985; Carballeira et al., 1993]. It is evident that these tests are not commonly used due to the simple fact that an extraction of pressboard material from transformers is not easily possible.

2.1.1 Analysis of oil

A physico-chemical analysis of oil usually consists of determination of the following properties:

- colour / appearance,
- water content,
- breakdown voltage,
- dielectric dissipation factor (tanδ) at temperatures 20-90 °C,
- acidity,
- interfacial tension.

These properties are measured with standardised test procedures and the required and recommended limit values for each test are given for new oils in [IEC 60296, 1982] and for oils in service in dependence upon category of equipments and voltage levels in [IEC 60422, 1989], see also [Sierota, Rungis, 1995; Knab, 1996].

In general, an intensification of oil colour is an indicator of oxidation (ageing). The quantification of oil colour by a colour test, using a table of colour or a colorimeter, is a simple method to assess the degradation of oil [ISO 2049, 1996]. The moisture content in oil is measured with Karl Fischer equipment, according to [IEC 60814, 1997].

The 50 Hz AC breakdown voltage and dielectric dissipation factor (tanδ) are useful properties to distinguish oils in good condition from deteriorated ones [Carod et al., 1993]. These quantities are good indicators of actual condition of oil, but they do not permit prognoses concerning progression of ageing. The precisely defined test procedures for determination of these properties are described in [IEC 60247, 1978; IEC 60156, 1995].
The acidity of oil is measured by a neutralization test, which consists in determination of the amount of potassium hydroxide necessary for neutralization of a 1 g oil sample. The neutralization number is expressed in mg KOH/g oil and is an efficient method to detect the presence of inorganic acids and to estimate the degree of oxidation. The recommended neutralization numbers for new and in-service oil are listed in [IEC 60296, 1982; IEC 60422, 1989].

Interfacial tension is a rather qualitative property, but a very sensitive indicator for the beginning of ageing. A decrease of interfacial tension is usually succeeded by a worsening of other dielectric properties [Carod et al., 1993; Knab, 1996].

The tests described above are methods to assess and follow the normal ageing procedure of oil-paper insulation in a fully serviceable transformer during several years of service. The quantities measured with these methods are quasi insensitive to local and acute irregularities such as hot spots or partial discharges in oil-paper insulation. The possibility to detect such failures exist with chromatographic analysis methods, Dissolved Gas Analysis (DGA) and High Performance Liquid Chromatography (HPLC), which permit to determine the dissolved gases and the cellulose decomposition products (furanic compounds) in oils.

The dissolved gas analysis permits to quantify different decomposition gases in oil as hydrogen, methane and other light hydrocarbons, the concentration and production rates of which are indicators of developing failures and irregularities in oil-paper insulation systems, such as hot spots, bad contacts, arcing or partial discharges [Knab et al., 1993; Knab 1996]. The procedure to perform this analysis is defined in [IEC 60567, 1992] and the interpretation of results are described in [IEC 60599, 1978]. Experience has demonstrated that in spite of existing standards, the correct judgement of the severity of a fault in a transformer is difficult due to the fact that the concentration of decomposition gases strongly depends on construction details and operation conditions of transformers. Therefore, according to new investigations [Knab, 1996], the evaluation of production rates of decomposition gases seems to be more indicative than that of their absolute concentration.

High performance liquid chromatography (HPLC) methods permit detection of the cellulose decomposition products (furanic compounds) in oil, which are a direct evidence of cellulose thermal degradation due to hot spots and partial discharges in cellulose. The HPLC is not a routine test, but it is normally recommended, when with the DGA method an unusually high concentration of carbon oxides, indicator for thermal degradation of cellulose, is detected [Knab et al., 1993; De Pablo et al., 1993; Knab 1996]. The analytical aspects of this method are defined in [IEC 61198, 1993].
2.1.2 "Component" diagnostic methods

Several conventional and unconventional dielectric test methods do exist, which are adapted for a direct application on power transformers and which permit assessing their insulation condition. These are mainly off-line electrical tests of non-destructive character. The conventional (traditional) quantities which are measured on transformers are:

- insulation (DC) resistance,
- polarization index,
- dielectric dissipation factor (tanδ),
- partial discharges.

The measurement of DC resistance is one of the oldest technique to evaluate the insulation condition of electrical components. The determination of a "true" DC resistance value is difficult due to the fact that the DC current generated by application of a DC voltage to the insulation system is always superimposed on the monotonically decreasing absorption (charging, polarization) current. For insulation systems in good condition, for example new transformers, the "true" DC regime is normally attained only after several hours. Therefore, in practice it is more common to determine the value of resistance after a well defined duration of voltage application. The usual ones are 1 min. and 10 min. resistances determined after 1 min. and 10 min. of voltage application, respectively. The measurement of insulation resistance is a simple technique for comparison of transformers of the same type or for controlling the evolution of insulation condition of a transformer during its service years.

The polarization index is defined as the ratio of the polarization current at 1 min. and 10 min. time intervals of DC voltage application. The inverse of polarization index is simply the ratio of 1 min. to 10 min. resistances of insulation. The polarization index and the derived quantity absorption current ratio, see [Manni, 1978], are successfully measured and evaluated on generators with their traditional micaceous insulation. For oil-paper insulation systems, the evaluation of these quantities has more significance for macroscopically homogeneous insulations such as impregnated paper as used in instrument transformers or cables. In case of power transformers with multi-layer insulation (pressboard barriers in series with oil ducts), these quantities are strongly influenced by macroscopic interfacial polarization (see section 7.3) and consequently by geometrical composition of insulation (volume ratio oil to pressboard).

The measurement of dielectric dissipation factor (tanδ) at power frequencies (50 Hz or 60 Hz) is a usual test, applied to different insulation parts of a transformer, including the high voltage bushings. The measured value of tanδ depends also on geometrical composition of oil-paper insulation. Therefore, just insulation systems with similar composition can be compared. The measurement of power frequency dissipation factor in dependence upon applied voltage level
can deliver additional information about insulation quality of investigated transformers [Porzel et al., 1996].

It is important to emphasize that all dielectric properties are temperature dependent and this fact must be considered during their measurement and evaluation. A temperature correction or conversion of measured quantities is only possible, when the geometrical composition of investigated insulation systems and the temperature dependence of the dielectric properties of their components, oil and paper, are known.

The detection of partial discharges, using an electrical and/or acoustic technique, is an effective diagnostic method to reveal incipient faults and local defects in HV insulation of power transformers. Today, significant partial discharges can even be detected under on-site conditions. This permits a quality control of strategically important new units after their installation in the field and a condition assessment of used transformers in service [Aschwanden et al., 1998].

The dielectric tests described above are approved in practice and have been widely used for many years. Besides these tests, there exist some unconventional techniques, which are well known from earlier times and have recently been readopted for investigation on power transformers. These methods consist of measurement and evaluation of time or frequency dependence of dielectric responses such as:

- recovery voltage and derived "polarization spectrum",
- relaxation / polarization and depolarization currents,
- complex capacitance (dielectric spectrum).

The measurement of dielectric response is not new, see historical overview in [Gross, 1986; Heizmann, 1994, section 4.4.1]. In the past, these methods were mainly used for dielectric investigations on laboratory samples and in rare cases also on electrical equipment such as cables or transformers [Fabre, 1954; Fabre, 1957a; Fabre, 1957b; Alekseev, 1958; Bouvier, Morel, 1966; Riaux, 1966; Occhini, Maschio, 1967]. New in this field is the adoption of modern sensing and computing techniques for a more efficient and precise application of these methods, especially for on-site application.

The quantification of the "polarization spectrum", obtained from individual recovery voltage measurements (see section 3.5), was proposed by [Bognar et al, 1990] for assessing the moisture content of pressboard embedded within the transformers. Meanwhile, the present investigations have demonstrated that the quantification of a pressboard moisture content, which is based on evaluation of the position in time of the main maximum in the "polarization spectrum" is incorrect (see sections 7.3.7 and 7.4.3). Contrary to statements as published in [Bognar et al, 1990; Tettex Instruments AG, 1992], this position in time is dependent on the composition of insulation (volume ratio oil to pressboard) and also on the dielectric properties of oil.
An important disadvantage of the determination of the "polarization spectrum" with a procedure as described in [Tettex Instruments AG, 1992] is the long measuring duration. The "polarization spectrum" is a derived quantity, it contains no additional information compared to the measured dielectric responses, e.g. recovery voltage or relaxation currents. In fact, based on linear models, the "polarization spectrum" can be calculated from a single measured relaxation current plot (see sections 3.9, 7.3.7 and 7.4.2) or from one or two measured recovery voltages [Helgeson, Gáfvert, 1995].

The measurement of relaxation currents is another technique of dielectric response quantification of power transformers in the time domain (see section 3.4). This method is well applicable under on-site conditions (see section 7.4) and the interpretation of resulting currents is easier than that of recovery voltage or the "polarization spectrum".

The direct measurement of complex capacitance (see section 3.6) or tanδ in dependence upon frequency (dielectric spectroscopy) on electrical equipment is still not widespread [Werelius et al, 1996; Neimanis, 1997]. This is mainly due to the limited availability of adequate portable instrumentation. The present investigations with a laboratory dielectric spectrometer [Pugh, 1984] on test transformers (see section 7.4.2) have demonstrated that the recorded spectra in the low frequency range can be calculated well from measured relaxation currents (see section 3.9). Such an indirect determination method of complex capacitance can well be integrated in a diagnostic tool based on measurement of relaxation currents [Der Houhanessian, Zaengl, 1996a; Aschwanden et al, 1998].

In general, the measured dielectric responses of power transformers, obtained by the methods listed above, can be described reasonably well by a linear model (see sections 3.11 and 7.4.3). For any quantitative analysis about the moisture content and ageing state of pressboard used in a power transformer, it is necessary to know the composition of the main insulation for distinguishing the dielectric response of pressboard from the total response of the insulation system (see section 7.4.3).
3 Theory of dielectric materials

In this chapter the basic relations of linear dielectric theory are listed and the definitions of measuring methods for quantification of dielectric response in the time or frequency domain are grouped. Also introduced are the linear models, which are presented in form of equivalent circuits and described by the corresponding linear relations.

3.1 Basic relations in the time domain

In vacuum the displacement (induction) $D(t)$ is proportional to the applied electric field $E(t)$, linked by the relation

$$D(t) = \varepsilon_0 E(t),$$

where $\varepsilon_0 = 8.854 \times 10^{-12}$ As/Vm is the permittivity of vacuum.

In presence of isotropic dielectric material, the displacement is increased by the polarization $P(t)$ of material to:

$$D(t) = \varepsilon_0 E(t) + P(t).$$

Here, $P(t)$ has a different time dependence than $E(t)$, but is still a linear function of $E(t)$, when the dielectric material is linear.

The isotropy and linearity of dielectric material are the conditions for the definition of all the following equations in this work.

The dielectric response function $f(t)$ is defined in terms of time dependence of polarization under an electrical field excitation in the form of a delta function of strength $(E\Delta t)$ [Jonscher, 1983]

$$P(t) = \varepsilon_0 (E\Delta t) f(t).$$

$f(t)$ is a monotonically decaying function and represents the impulse response of dielectric material.

For an arbitrary time dependent electrical field $E(t)$, the polarization $P(t)$ is then related to the dielectric response function $f(t)$ by the convolution

$$P(t) = \varepsilon_0 \int_{-\infty}^{t} f(t-\tau)E(\tau)d\tau = \varepsilon_0 \int_{0}^{t} f(\tau)E(t-\tau)d\tau. $$

In case of a step excitation at time $t = 0$ with a constant amplitude $E_c$, the polarization $P(t)$ becomes:

$$P(t) = \varepsilon_0 E_c \int_{0}^{t} f(t)dt = \varepsilon_0 E_c h(t).$$
The function \( h(t) \) represents the step response of the dielectric material (see figure 1); its value for \( t \to \infty \) is finite and is proportional to the real part of the dielectric susceptibility at frequency zero, \( \chi'(\omega = 0) \), see relation (9).

\[
\begin{align*}
\text{Figure 1: Polarization of a dielectric material exposed to an electrical step field.}
\end{align*}
\]

According to [Maxwell, 1891] an electrical field \( E(t) \) applied at time \( t = 0 \) to a dielectric material generates a current density \( j(t) \), which can be written as a sum of conduction current and displacement current:

\[
j(t) = \sigma_0 E(t) + \frac{dD(t)}{dt},
\]

where \( \sigma_0 \) is the DC conductivity of the dielectric material.

Using the relations (2) and (4) the current density can be expressed as:

\[
j(t) = \sigma_0 E(t) + \varepsilon_0 \frac{dE(t)}{dt} + \varepsilon_0 \frac{d}{dt} \int_0^t f(t - \tau) E(\tau) d\tau
\]

\[
= \sigma_0 E(t) + \varepsilon_0 \frac{dE(t)}{dt} + \varepsilon_0 f(0) E(t) + \varepsilon_0 \int_0^t \frac{df(t - \tau)}{dt} E(\tau) d\tau.
\]

For the special case of a step excitation with amplitude \( E_c \), equation (7) becomes:

\[
j(t) = \sigma_0 E_c + \varepsilon_0 E_c [\delta(t) + f(t)],
\]

where \( \delta(t) \) is the delta function.
3.2 Basic relations in the frequency domain

The frequency dependent susceptibility $\chi(\omega)$ is defined as the Fourier transform of the dielectric response function $f(t)$:

$$\chi(\omega) = \chi'(\omega) - i\chi''(\omega) = \int_0^{\infty} f(t) \exp(-i\omega t) dt.$$  \hspace{1cm} (9)

Then, in the frequency domain the polarization can be written as:

$$\mathbf{P}(\omega) = \varepsilon_0 \chi(\omega) \mathbf{E}(\omega).$$  \hspace{1cm} (10)

The equation (6) can be expressed in the frequency domain according to the Fourier transform as:

$$j(\omega) = \sigma_0 \mathbf{E}(\omega) + i\omega \mathbf{D}(\omega).$$  \hspace{1cm} (11)

Using the equations (2) and (9) the current density is re-written as:

$$j(\omega) = \{\sigma_0 + i\omega \varepsilon_0 [1 + \chi'(\omega) - i\chi''(\omega)]\} \mathbf{E}(\omega)$$

$$= \{\sigma_0 + \varepsilon_0 \omega \chi''(\omega) + i\omega \varepsilon_0 [1 + \chi'(\omega)]\} \mathbf{E}(\omega).$$  \hspace{1cm} (12)

The relative dielectric permittivity of material $\varepsilon_r(\omega)$ is defined by the relation:

$$\mathbf{D}(\omega) = \varepsilon_0 \varepsilon_r(\omega) \mathbf{E}(\omega) = \varepsilon_0 [1 + \chi'(\omega) - i\chi''(\omega)] \mathbf{E}(\omega)$$  \hspace{1cm} (13)

and can be expressed as:

$$\varepsilon_r(\omega) = \varepsilon'_r(\omega) - i\varepsilon''_r(\omega) = 1 + \chi'(\omega) - i\chi''(\omega).$$  \hspace{1cm} (14)

For a practical determination of the dielectric response from equation (12), a bridge or any other instrument cannot distinguish between the current contribution of DC conductivity and that of dielectric loss. This means that the effective measured relative dielectric permittivity $\tilde{\varepsilon}_r(\omega)$ is different from the relative permittivity $\varepsilon_r(\omega)$ defined in equations (13) / (14).

The effective relative dielectric permittivity $\tilde{\varepsilon}_r(\omega)$ measured can be given from the relation

$$j(\omega) = i\omega \varepsilon_0 \tilde{\varepsilon}_r(\omega) \mathbf{E}(\omega)$$  \hspace{1cm} (15)

as:

$$\tilde{\varepsilon}_r(\omega) = \varepsilon'_r(\omega) - i[i\varepsilon''_r(\omega) + \sigma_0 / \varepsilon_0 \omega]$$

$$= 1 + \chi'(\omega) - i[\chi''(\omega) + \sigma_0 / \varepsilon_0 \omega]$$  \hspace{1cm} (16)

The dissipation factor or $\tan\delta$ can then be defined from equation (16) as:

$$\tan\delta(\omega) = \frac{\varepsilon''_r(\omega) + \sigma_0 / \varepsilon_0 \omega}{\varepsilon'_r(\omega)}.$$  \hspace{1cm} (17)
3.3 Practical considerations

For practical application of equation (2) it is important to realize that for an adequate step excitation the initial part of the polarization is usually so large and transient that it cannot be sensed or resolved. This so called "fast" or "instantaneous" polarization can be taken into account by multiplying the first term of equation (2) with the real part of the relative dielectric permittivity, \( \varepsilon'_r \), which dominates at high frequencies. Then, with the remaining contribution of "slow" polarization, the equation (2) can be re-written as:

\[
D(t) = \varepsilon_0 \varepsilon'_r E(t) + P(t). \tag{18}
\]

For convenience, \( \varepsilon'_r \) is just marked as \( \varepsilon_r \) in the following equations and it is simply called relative permittivity. To emphasize the fact that \( \varepsilon_r \) is a frequency and temperature dependent quantity, it is explicitly avoided to use the term "dielectric constant", which was, however, used in [Jonscher, 1983]. For the application of equation (18) for times greater than 1 second, it is sufficient to determine \( \varepsilon_r \) at power frequencies of 50 or 60 Hz.

For a homogeneous material, the field strength \( E(t) \) can be considered as generated by an external voltage \( u(t) \). Then, the generated current \( i(t) \) can be re-written from equation (7) as:

\[
i(t) = C_0 \left[ \sigma_0 \frac{\partial u(t)}{\partial t} + \varepsilon_r \frac{\partial u(t)}{\partial t} + \frac{d}{dt} \int_0^t f(t - \tau) u(\tau) d\tau \right]
\]

\[
= C_0 \left[ \sigma_0 \frac{\partial u(t)}{\partial t} + \varepsilon_r \frac{\partial u(t)}{\partial t} + \frac{d}{dt} \int_0^t f(t - \tau) u(\tau) d\tau \right], \tag{19}
\]

where \( C_0 \) is the geometric or vacuum capacitance of the test object investigated.

It is important to emphasize that this equation is also valid for an arrangement of several dielectric materials in series or in parallel, which is considered as a "black box". In this case \( \sigma_0, \varepsilon_r \) and \( f(t) \) represent a comprehensive DC conductivity, relative permittivity and dielectric response function of this heterogeneous test object.
3.4 Relaxation currents

The polarization in materials cannot be measured directly, but a simple method to observe its development in time is the measurement of the so-called relaxation (polarization- / depolarization; charging- / discharging; absorption- / desorption) currents generated from a step excitation of amplitude $U_c$ and the subsequent short-circuiting, see figure 2. The polarization current $i_{\text{pol}}(t)$ during the constant excitation, which starts at a time instant $t = 0$, is expressed from equation (19) as:

$$i_{\text{pol}}(t) = U_c C_0 \left[ \sigma_0 \varepsilon_0 + f(t) \right] . \tag{20}$$

According to the superposition principle, the depolarization current $i_{\text{depol}}(t)$ after the short-circuit is given by:

$$i_{\text{depol}}(t) = -U_c C_0 \left[ f(t) - f(t + T_c) \right] , \tag{21}$$

where $T_c$ is the duration of time during which the voltage had been applied to the test object. As $f(t)$ is a monotonically decaying function, the second term in equation (21) can be neglected for large values of $T_c$ and the depolarization current becomes proportional to the dielectric response function.

**Figure 2**: Principle of relaxation current measurement.
3.5 Recovery voltage and "polarization spectrum"

The measurement of recovery or return voltages is another method to quantify the dielectric response of materials. The principle of the measurement is as follows (see figure 3): A constant voltage $U_c$ charges the test object for $0 \leq t < t_1$; after a short-circuit period between $t_1 \leq t < t_2$, the test object is left in open-circuit condition. For times $t \geq t_2$ a recovery voltage $u_r(t)$ caused by residual polarization is built up across the test object, which on its part becomes re-polarized again. The test object is discharged under this condition by its own DC conduction. If the dielectric response function of the test object is known, the time dependence of recovery voltage for $t \geq t_2$ can be described by the following relation, which can be derived from equation (19) [Ildstad et al., 1994; Jonscher, 1996].

\[
\frac{\sigma_0}{\varepsilon_0} u_r(t) + \varepsilon_r \frac{du_r(t)}{dt} + f(0)u_r(t) + \\
U_c[f(t) - f(t - t_1)] + \int_{t_1}^{t} \frac{df(t - \tau)}{dt} u_r(\tau) d\tau = 0
\]  

(22)

with the initial condition $u_r(t_2) = 0$.

Figure 3: Principle of recovery voltage measurement.

The so called "polarization spectrum" [Bognar et al., 1990] is a derived quantity from a special measurement procedure of recovery voltages. It is determined from maxima of many recovery voltages, which can be recorded in dependence on charging duration. These maxima are then presented as a function of increasing charging duration. Conventionally, a ratio of 2 [Bognar et al., 1990] has been chosen between charging $T_c$ and discharging $T_d$ duration.
3.6 **Complex capacitance**

The complex capacitance $C(\omega)$ is the quantity, which can be measured directly with a dielectric spectrometer [Pugh, 1984] and is defined from the relation between the measured current $I(\omega)$ and the measured voltage $U(\omega)$ as:

$$ I(\omega) = i\omega C(\omega) U(\omega). $$

(23)

According to equation (15), it is related to relative dielectric permittivity by:

$$ C(\omega) = C'(\omega) - iC''(\omega) = C_0 \left\{ \varepsilon'_r(\omega) - i\left[ \varepsilon''_r(\omega) + \sigma_0/\varepsilon_0 \omega \right] \right\}. $$

(24)

Here, $C_0$ and $\sigma_0$ again represent the vacuum or geometric capacitance and DC conductivity of test object, respectively.

The dissipation factor $\tan\delta(\omega)$ can be re-written using equation (17) as:

$$ \tan\delta(\omega) = \frac{C''(\omega)}{C'(\omega)}, $$

(25)

as the loss due to DC conductivity is included in $C''(\omega)$.

3.7 **DC conductivity**

The DC conductivity can be determined from dielectric responses in the time or frequency domain. By definition, its direct determination is carried out in the time domain by the measurement of the DC component of polarization current. For highly resistive dielectric materials (for example polyethylene), this method of determination involves some difficulties due to the extremely long time necessary for the polarization current to reach the DC value, and due to its low amplitude.

In the frequency domain, the DC conductivity can be determined from the measured complex capacitance, see equation (24), using Kramers-Kronig relation to separate the DC conductivity contribution from the imaginary part of complex capacitance $C''$ [Jonscher, 1983].

A simple but adequate approximation of the DC conductivity can be made from relaxation currents, using the following relation:

$$ \sigma_0 = \frac{\varepsilon_0}{U_c C_0} [i_{pol}(t_m) + i_{depol}(t_m)], $$

(26)

where $t_m$ represents the largest value of time, for which the relaxation currents have been measured. It is obvious that this approximation is more precise for larger charging durations (see equations (20) and (21)). A simple solution to the problem of limited charging duration is the extrapolation of the measured polarization current to a DC regime for long times. Another solution is the calculation of a new depolarization current for an infinite charging duration from the equivalent circuit as introduced for a sample investigated (see section 3.9) and
its subtraction from the measured polarization current. According to relations (20) and (21), it can be written

$$\sigma_0(t) = \frac{\varepsilon_0}{U_C C_0} [i_{\text{pol}}(t) + i_{\text{depol}}^*(t)],$$

(27)

where $i_{\text{depol}}^*(t)$ is the depolarization current calculated for an infinite charging duration. This current is theoretically equal to

$$i_{\text{depol}}^*(t) = -[i_{\text{pol}}(t) - \frac{\sigma_0}{\varepsilon_0}].$$

(28)

As already indicated in equation (27), the determined conductivities $\sigma_0(t)$ are time dependent. A cause of this time dependence is the low amplitude of calculated currents $i_{\text{depol}}^*(t)$ for large times in contrast to the "true" depolarization currents expected with an infinite charging duration. This is simply due to the fact that the equivalent circuits determined from depolarization currents with a finite charging duration do not contain all information about the entire polarization processes. Other causes of this time dependence are the limited time and amplitude accuracy of the relaxation currents measured and finally, the non-perfect "linear" behaviour of samples investigated. This time dependence is especially accentuated for multi-layer samples (pressboard disks in series with oil gaps).

The conductivities of the pressboard samples in this work are determined from relaxation currents, evaluating the relations (27) for the largest instants of time, for which the currents have been measured. A sufficiently good approximation for the DC conductivity of multi-layer samples of relatively high conductivity and service aged power transformers was made from relation (26), using the relaxation currents with a charging duration of 5'000 s. For highly resistive multi-layer samples and for new power transformers, an extrapolation of the registered polarization currents was necessary to obtain more accurate values of DC conductivity.

The measurement of oil conductivity close to its thermodynamic equilibrium of charge carrier dissociation and recombination presents some experimental problems [Gäfvert et al., 1986; Hilaire et al., 1988]. In particular, this equilibrium is modified by application of high amplitude DC voltages for a long time due to the phenomena of charge injection at electrodes, charge generation in bulk oil and charge accumulation at electrodes. Therefore, for determination of conductivity with the DC method, it is very important to use low voltage levels to avoid non-linear and electrode effects. It is also important to determine the conductivity from the initial values of generated current. In fact, the current generated at short times represents the conduction current of drifting ionic impurities and thus reflects the loss current component measured with AC voltage at power frequency. Besides the classic DC and AC voltage methods, also some combined low voltage, low frequency methods are in use, which allow one to determine the conductivity of oil as close as possible to its thermodynamic equilibrium with
sufficient accuracy [Gäfvert et al., 1986; Tobazéon et al., 1994; Li, Rungis, 1997]. In section 7.2 a comparison between low DC voltage and "triangular wave" methods [Gäfvert et al., 1986] is presented.

### 3.8 Temperature-dependent behaviour of dielectric materials

It is well known that dielectric responses are significantly influenced by the temperature. This influence can be characterized for impregnated pressboard by activation energies for dielectric loss and DC conductivity. Frequency domain investigations on pressboard samples confirmed that a change of temperature will shift the spectra of susceptibility (real and imaginary parts) along the frequency axis. The general shape of the spectra, however, remains the same. The temperature dependence of loss can be determined from frequency shifts, necessary to obtain coincidence of the spectra measured at different temperatures, leading to a single spectrum, the so called "master curve" [Jonscher, 1983; Sheiretov, Zahn, 1995]. These shifts \( S(T) \) obeyed a quasi-exponential law given as:

\[
S(T) = \exp\left(-\frac{E_{al}}{kT}\right)
\]

where \( T \) is the absolute temperature in Kelvin, \( k = 1.381\times10^{-23} \text{ JK}^{-1} = 8.62\times10^{-5} \text{ eVK}^{-1} \) is the Boltzmann constant and \( E_{al} \) is the activation energy for dielectric loss.

In the time domain, according to the theory of Fourier transforms, this procedure corresponds to a shift of the dielectric response functions or the depolarization currents measured with a long charging duration along a line with a slope of \(-1\) in the double logarithmic plot.

The temperature behaviour of DC conductivity of pressboard can also be described by an exponential law given as:

\[
\sigma_0(T) = \exp\left(-\frac{E_{ac}}{kT}\right),
\]

which can also be characterized by its activation energy \( E_{ac} \).

For investigations in this work, the mineral oil is simply characterized by its relative permittivity at power frequency and its conductivity (see section 7.2). The temperature dependence of oil conductivity also obeys a quasi-exponential law [Diabi et al., 1996]. The relative permittivity of oil at power frequency decreases with an increase of temperature. For temperatures above 0 °C, this decrease is mainly caused by the volume expansion of oil [von Münch, 1987; Bartnikas, 1994].
3.9 Modelling

Within this work, the relaxation current measurements always commence about 1 s after the step voltage or the short-circuit application; this means that even power frequencies (50...60 Hz) are not included, if the frequency domain is considered. As, in general, all relaxation currents decayed monotonously, a well known equivalent circuit representing the insulation system was adopted, which is shown in figure 4. It is also commonly known that dielectrics with alternating layers of oil and paper can be well simulated with this model [Alekseev, 1958; Occhini, Maschio, 1967]. The basic idea in applying this simple model is to facilitate all further calculations with respect to the frequency domain or even the calculation of a "polarization spectrum" belonging to the special procedure of recovery voltage measurements.

![Figure 4: Equivalent circuit to model a linear dielectric](image)

For this model, all circuit parameters are determined by quantities measured, such as the polarization and depolarization currents, \( i_{\text{pol}}(t) \) and \( i_{\text{depol}}(t) \), and the capacitance \( C_{50\text{ Hz}} \) as determined by conventional C-measurements with power frequency (50...60 Hz) or even some higher frequencies (e.g. 1 kHz), which usually give quite similar values of \( C \). The DC resistance \( R_0 \) can be approximated from the applied step voltage \( U_c \) and the difference between polarization and depolarization currents for the highest available time values (see section 3.7). The individual elements \( R_i, C_i \) with the corresponding time constants \( \tau_i = R_i \cdot C_i \) can then be determined by fitting the depolarization current with the equation

\[
i_{\text{depol}}(t) = \sum_{i=1}^{n} A_i \exp(-t/\tau_i), \tag{31}\]

where

\[
A_i = U_c [1 - \exp(-T_c/\tau_i)]/R_i, \quad \text{for } i = 1...n \tag{32}
\]

and \( T_c \) is the duration of the time, during which the sample was charged.

The coefficients \( A_i \) and the time constants \( \tau_i \) in equation (31) are determined by using a special sequential algorithm, which is described as follows: In the first step of calculation a series of time constants \( \tau_i \) are chosen, the values of which are
distributed "equidistantly" in the logarithmic time scale over which the depolarization current has been recorded. Usually two or three time constants per decade are sufficient to fit the measured depolarization current with sufficiently high accuracy (see section 7.1.6). The unknown coefficients $A_i$ of equation (31) with time constants so chosen are then determined with the least squares method from current data recorded. In a second step, equation (31) is re-defined, eliminating all terms with negative coefficients from the previous equation. A further calculation with the least squares method determines now the new coefficients $A_i$ of the remaining terms. The second step is repeated until all remaining coefficients in equation (31) are positive. Normally, less than five steps are necessary to achieve this goal. It is obvious that remaining time constants have no physical significance.

For this equivalent circuit the complex capacitance $C(\omega)$ can be calculated according to equation (23) from its complex admittance, $Y(\omega)$ as:

$$C(\omega) = \frac{Y(\omega)}{i\omega} = C_{50Hz} + \frac{1}{i\omega R_0} + \sum_{i=1}^{n} \frac{C_i}{1 + i\omega R_i C_i}$$  \hspace{1cm} (33)

The real and imaginary parts of $C(\omega)$ are then given as:

$$C'(\omega) = C_{50Hz} + \sum_{i=1}^{n} \frac{C_i}{1 + (\omega R_i C_i)^2}$$  \hspace{1cm} (34)

and

$$C''(\omega) = \frac{1}{\omega R_0} + \sum_{i=1}^{n} \frac{\omega R_i C_i^2}{1 + (\omega R_i C_i)^2}.$$  \hspace{1cm} (35)

The $\tan \delta(\omega)$ can be written as:

$$\tan \delta(\omega) = \frac{1}{\omega R_0} + \sum_{i=1}^{n} \frac{\omega R_i C_i^2}{1 + (\omega R_i C_i)^2}.$$  \hspace{1cm} (36)

The building up of the recovery voltage, as described in section 3.5, for times $t \geq t_2$ can be calculated from a system of the following differential equations:

$$\frac{du_i(t)}{dt} = \frac{1}{R_i C_i} [u_i(t) - u_i(t)], \hspace{1cm} \text{for } i = 1 \ldots n$$  \hspace{1cm} (37)

and

$$\frac{du_i(t)}{dt} = \frac{1}{C_{50Hz} R_0} \left[ -\frac{u_i(t)}{R_0} - \sum_{i=1}^{n} \frac{u_i(t) - u_i(t)}{R_i} \right],$$  \hspace{1cm} (38)
where \( u_i(t) \) is the voltage across the test object and \( u_i(t) \) are voltages across the capacitances \( C_i \). To solve this system of differential equations, \( n+1 \) values of voltages \( u_i(t) \), for \( i=1...n \), and \( u_i(t) \) at time \( t=t_2 \) are necessary. These values are given as:

\[
 u_i(t_2) = U_c[1 - \exp(-T_c/R_iC_i)] \exp(-T_d/R_iC_i) \tag{39}
\]

and

\[
 u_i(t_2) = 0, \tag{40}
\]

where \( U_c \) is the amplitude of the charging voltage, \( T_c \) and \( T_d \) are the charging and discharging duration, respectively (see figure 3).

It is important to emphasize that this simple equivalent circuit also describes quite well the dielectric behaviour of a multi-layer test object consisting of pressboard sheets in series with oil ducts, but it does not permit one to determine the individual dielectric response functions of each material or to quantify the interfacial polarization [von Hippel, 1966; Fournié, 1986].

3.10 Dielectric response of multi-layer materials

To identify the individual dielectric response of each material or the interfacial polarization of a multi-layer test object with \( m \) materials in series, it is imperative to know the local voltages \( u_k(t) \) on materials \( k=1...m \). The local voltages \( u_k(t) \) can be calculated from a system of equations formed by the conditions of total voltage and of current continuity in a series arrangement:

\[
 \sum_{k=1}^{m} u_k(t) = u(t) \tag{41}
\]

and

\[
 i_1(t) = \cdots = i_k(t) = \cdots = i_m(t), \tag{42}
\]

where \( u(t) \) is the total voltage applied on the test object and \( i_k(t) \) are the local currents in materials \( k=1...m \). The relationships between the current \( i_k(t) \) and the voltage \( u_k(t) \) of each material \( k \) can then be written analogous to equation (19) as:

\[
 i_k(t) = C_{0k} \left[ \frac{\sigma_{0k}}{\varepsilon_0} u_k(t) + \varepsilon_{rk} \frac{du_k(t)}{dt} + \int_0^1 f_k(t-\tau)u_k(\tau)d\tau \right], \tag{43}
\]

for \( k=1\cdots m \),

where \( C_{0k} \) is the geometric capacitance of material \( k \) and \( \sigma_{0k}, \varepsilon_{rk} \) and \( f_k(t) \) represent the DC conductivity, the relative permittivity and the dielectric response function of material \( k \), respectively.
In terms of equivalent circuits, this system of equations can also be represented with an "extended" equivalent circuit formed from a series connection of \( m \) equivalent circuits as shown in figure 4, see figure 5.

![Figure 5: "Extended" equivalent circuit to model a linear multi-layer dielectric.](image)

### 3.11 Modelling of power transformers

The typical winding configuration of one phase of a power transformer is based on a low voltage winding which is nearest to the limb of the core, surrounded by the high voltage winding, which is separated from the former one by the main duct. This duct comprises a series of pressboard barriers with oil ducts in between and axial pressboard spacers to fix the barriers mechanically. As a typical relaxation current measurement is performed by applying a DC voltage to the HV winding with the current sensing between the LV winding and earth, the current measured is essentially produced by the composite insulation system between both windings, which is of a coaxial configuration.

Figure 6 shows a section of such a geometry. As the axial dimension of the windings is in general much larger than the radial distance between the windings, the influence of the insulation between the windings and the yokes of the iron core can usually be neglected.
Figure 6: The cross-section of the main insulation between low and high voltage windings of a power transformer.

With this simplification of a structure of the geometrical layout, which is in reality more complex, the main insulation can be subdivided into three components, lumping all oil ducts, all barriers and all spacers together, to form one oil duct in series with a single barrier and parallel to this, a single spacer. Therefore, the "extended" equivalent circuit used for modelling of the main insulation will also contain three subsystems as shown in figure 7. The parallel position of a spacer component in this model disclosed the fact that the short barrier segments, which are situated between the spacers (see figure 6), are included in this component. This inclusion is done with the assumption that the constituent pressboard materials of the barriers and spacers have the same dielectric properties. In the equivalent circuit presented in figure 7, the oil duct is just simulated by its resistance $R_D$ and the capacitance $C_D$. Such a simplified equivalent circuit is justified as transformer oil has no dispersion within the frequency range of interest, i.e. for frequencies approximately equal to or lower than the power frequency (see section 7.2). As the geometric or vacuum capacitance of the oil duct $C_{0D}$ can readily be calculated from the geometric configuration, the values for $R_D$ and $C_D$ can be determined by means of the following two equations:

$$R_D = \frac{\varepsilon_0}{\sigma_{\text{oil}} \cdot C_{0D}} \quad (44)$$

and

$$C_D = \varepsilon_{\text{oil}} \cdot C_{0D} \cdot (45)$$
Here, $\sigma_{\text{oil}}$ and $\varepsilon_{\text{oil}}$ are the conductivity and relative permittivity of oil, respectively.

\[ \text{Oil duct} \quad \text{Pressboard spacer} \]

\[ \begin{array}{c}
\text{u}_D \quad R_D \quad C_D \\
\text{i}_\text{D} \\
\text{u}_B \quad R_B \quad C_B \\
\text{i}_B \\
\end{array} \quad \begin{array}{c}
\text{R}_S \quad C_S \\
\text{R}_{S1} \quad C_{S1} \\
\text{R}_{S2} \quad C_{S2} \\
\text{i}_S \\
\end{array} \]

\[ \text{Pressboard barrier} \]

Figure 7: "Extended" equivalent circuit of the main insulation of a power transformer.

The pressboard barrier and the spacer are first of all modelled (figure 7) in the same way by their DC resistances, $R_B$ and $R_S$, and their power frequency capacitances, $C_B$ and $C_S$, determined from DC conductivity $\sigma_{\text{opb}}$ and relative permittivity $\varepsilon_{\text{opb}}$ of pressboard and their geometrical capacitances, $C_{0B}$ and $C_{0S}$. The dielectric dispersion of pressboard, which is a key quantity in these investigations, is represented by a number of $n$ parallel arrangements of RC elements, which simulate the dielectric response function. The values of these elements can be calculated from the relaxation currents previously measured on pressboard samples, once more taking the factor of geometrical capacitance into account.

For this equivalent circuit, the generated polarization or charging current through the main insulation for a constant step voltage $U_c$ can also be described by well known equations of linear dielectric theory. Then, the total polarization current $i_{\text{pol}}(t)$ (see figure 7) through the main insulation is given as a sum of currents $i_D(t)$ in the oil duct and $i_S(t)$ in the pressboard spacer:

\[ i_{\text{pol}}(t) = i_D(t) + i_S(t). \] (46)
The current $i_s(t)$ is related to the step voltage $U_c$ by

$$i_s(t) = U_c \left[ \frac{1}{R_S} + \frac{C_S}{\varepsilon_{tpb}} f_{pb}(t) \right], \quad (47)$$

where $f_{pb}(t)$ is the dielectric response function of pressboard.

The current $i_D(t)$ through the oil duct can be calculated for the step voltage $U_c$ applied, according to the following system of equations:

$$i_D(t) = \frac{u_D(t)}{R_D} + C_D \frac{d u_D(t)}{dt}, \quad (48)$$

$$i_B(t) = \frac{u_B(t)}{R_B} + C_B \frac{d u_B(t)}{dt} + \frac{C_B}{\varepsilon_{tpb}} \frac{d}{d t} \int_0^t f_{pb}(t - \tau) u_B(\tau) d\tau, \quad (49)$$

with the conditions of current continuity and total voltage

$$i_D(t) = i_B(t) \quad (50)$$

$$U_c = u_D(t) + u_B(t). \quad (51)$$

In these equations, $i_B(t)$ is the current through the pressboard barrier, $u_D(t)$ and $u_B(t)$ are the voltages across the oil duct and the pressboard barrier, respectively.

The subsequent depolarization current $i_{depol}(t)$ as measured when the main insulation is short-circuited can be calculated from the polarization current $i_{pol}(t)$, applying the superposition principle. Analogous to equation (21), the following relation can be written:

$$i_{depol}(t) = -[i_{pol}(t) - i_{pol}(t + T_c)], \quad (52)$$

where $T_c$ is the duration of the preceding voltage application.
4 Test objects investigated

The investigations in laboratory set-ups are carried out on macroscopically homogeneous samples of impregnated pressboard and mineral oil but also on multi-layer samples consisting of a series arrangement of pressboard disks and oil ducts. The measurements are carried out in dependence on parameters such as moisture content and ageing products in pressboard and mineral oil, geometrical layout (volume ratio oil to pressboard) and temperature. The investigations on "real" test objects are performed on new and used power transformers under laboratory and field conditions.

4.1 Laboratory samples

The descriptions of laboratory samples investigated and their preparation procedures are presented in following three sections 4.1.1 to 4.1.3.

4.1.1 Pressboard samples

The dielectric behaviour of impregnated pressboard in dependence on moisture content and ageing is determined from round disks of Weidmann pressboard, Transformerboard Type TIV, with a diameter of 160 mm and thicknesses of 1 mm, 2 mm and 3 mm. For impregnation a degassed and dried Technol US 3000 mineral oil was used (moisture content: < 5 ppm). The first set of samples was prepared in the central laboratory of the Weidmann company. The preparation of new (unaged) samples with moisture contents of 0.2%, 1.0%, 2.5% and 5.0% was as follows: For each moisture level several disks of pressboard with 1 mm, 2 mm and 3 mm thickness were dried under vacuum (< 1 mbar) for 24 hours at 105 °C. Afterwards they have been exposed to ambient air. The moisture absorption was continuously checked by weighing of one sample of each thickness. On reaching the desired moisture level, the samples were stored, hermetically sealed, for one week before impregnation. With this procedure, the moisture distribution within the samples became more uniform. The impregnation was carried out under ambient air pressure. After impregnation the samples have been stored in stainless steel vessels, completely filled with oil and closed hermetically (see figure 8, cylindrical vessel). The weight ratio of oil to pressboard in these vessels was 8.4 (weight of pressboard: 1'400 g).

The given moisture content value of a sample is defined as the percent ratio of water weight absorbed from the sample to its dried non-impregnated weight. According to specification of Weidmann AG, the moisture content of dried samples with the above procedure (24 hours at 105 °C under vacuum) can be assumed to be lower than 0.2%. Therefore, the moisture content of present "dry" samples is given as 0.2%.
In addition to new (unaged) samples, two series of aged samples were also prepared by the Weidmann company. The ageing procedure was as follows: Two additional vessels, containing pressboard samples with moisture contents of 0.2% and 1.0%, respectively, were prepared. To reproduce typical conditions in a transformer tank, 60 g copper and 45 g core iron plates were also added to each vessel. A thermal ageing procedure was performed, by placing the hermetically sealed vessels, equipped with extension chambers, in an oven at a constant temperature of 120°C for a duration of 90 days. The ageing process increased the moisture content of the pressboard as measured by a Karl Fischer equipment (a Mitsubishi CA-05 Moisture Meter equipped with a VA-05 Vaporizer) from 0.2% to 0.5% and from 1.0% to 2.0% [Scholz, 1984; IEC 60814, 1997]. The moisture content of the oil increased from its initial values of about 5 ppm in both vessels to 9 ppm and 19 ppm, respectively. The degree of depolymerization (DP-value) during ageing changed from an initial value of 950 for new samples to 479 and 195 for aged samples with 0.5% and 2.0% moisture content, respectively, according to [IEC 60450, 1974].

![Metallic vessels used for conservation of impregnated pressboard samples.](image)

**Figure 8:** Metallic vessels used for conservation of impregnated pressboard samples.

To perform additional investigations concerning the transient behaviour of samples due to internal moisture distribution and to control the absolute values of quantities measured, a second set of samples with moisture contents of 1.0%, 2.5%, 4.0% and 4.9% was prepared later in the ETHZ laboratory. This time,
moisture setting was performed individually for each sample with the procedure described above. The temperature and the relative humidity of ambient air were taken as constant during the moistening, at 20 °C and 60%. To study the transient behaviour of samples due to the non-uniform distribution of moisture, samples with the same moisture content were either impregnated immediately after moisture setting or after a week of hermetically sealed off storage. This time, the samples with the same moisture content were conserved after impregnation in oil filled flat aluminium vessels to keep the volume ratio of oil to pressboard low (see figure 8).

4.1.2 Oil samples

Dielectric measurements have been performed on several new mineral oil samples (Technol US 3000, Shell Diala C, etc.) but also on samples taken from transformers investigated.

4.1.3 Oil-paper multi-layer samples

Investigations have also been carried out on 3-layer arrangements in which two pressboard disks are placed on the surface of parallel-plate electrodes, separated by a central oil duct of variable thickness (see figure 9). The disks have been

Figure 9: Investigated 3-layer arrangement built up between parallel-plate electrodes.
separated and fixed with Teflon spacers which were positioned near the rim of the disks.

For this investigation, the used oil and pressboard samples belonged always to the same "systems", which were conserved together in cylindrical vessels as described before.

4.2 Power transformers

Several new and service-aged transformers (over 40 units) have been investigated either in the test laboratory of the manufacturer or under on-site conditions within outdoor or indoor stations owned by utilities. Measurements have been performed on several presumably identical units. Transformers have been investigated before and after overhaul. Some new units have been measured twice, first at manufacturer's premises and then after their installation in the field. The new and service-aged transformers investigated in this work are listed in tables 1 and 2.

Table 1: Investigated new transformers.

<table>
<thead>
<tr>
<th>Pos.</th>
<th>Number of tested units</th>
<th>Description of transformer</th>
<th>Year of constr.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>single-phase 16-2/3 Hz 132+6–14×2/16 kV 21.8 MVA</td>
<td>1995</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>3-phase 50 Hz 64.2±9×0.8/18.7 kV 25 MVA</td>
<td>1995</td>
</tr>
<tr>
<td>3</td>
<td>2</td>
<td>3-phase 50 Hz 51.4±11×0.6/13.6–21 kV 25 MVA</td>
<td>1996</td>
</tr>
<tr>
<td>4</td>
<td>1</td>
<td>3-phase 50 Hz 132±11×1.6/12.2 kV 31.5 MVA</td>
<td>1996</td>
</tr>
<tr>
<td>5</td>
<td>1</td>
<td>3-phase 50 Hz 241±11×3.5/120/16.5 kV 160/160/53.3 MVA</td>
<td>1996</td>
</tr>
<tr>
<td>6</td>
<td>1</td>
<td>3-phase 50 Hz 245/155±10×1.5/20 kV 400/400/100 MVA</td>
<td>1996</td>
</tr>
<tr>
<td>7</td>
<td>2</td>
<td>a group of 3-phase 50 Hz 400/242±17×2.3/16 kV 400/400/120 MVA regulating transformers, consisting of a 3-phase main unit and a 3-phase regulating unit.</td>
<td>1994</td>
</tr>
<tr>
<td>8</td>
<td>6</td>
<td>a group of 3-phase 50 Hz 400/247±17×3.6/30 kV 600 MVA regulating transformers, consisting of 3 single-phase main units and 3 single-phase regulating units.</td>
<td>1996</td>
</tr>
</tbody>
</table>
Table 1 (continued): Investigated new transformers.

<table>
<thead>
<tr>
<th>Pos.</th>
<th>Number of tested units</th>
<th>Description of transformer</th>
<th>Year of constr.</th>
</tr>
</thead>
<tbody>
<tr>
<td>9</td>
<td>8</td>
<td>a group of 3-phase 50 Hz 400/247±11×3.6/50 kV 600 MVA regulating transformers with spare pole, consisting of 4 single-phase main units and 4 single-phase regulating units.</td>
<td>1996</td>
</tr>
<tr>
<td>10</td>
<td>1</td>
<td>a group of 3-phase 50 Hz 400/245+9—7×2.5/30 kV 800/800/80 MVA power transformers, consisting of 3 single-phase units.</td>
<td>1995</td>
</tr>
</tbody>
</table>

Table 2: Investigated service-aged transformers.

<table>
<thead>
<tr>
<th>Pos.</th>
<th>Number of tested units</th>
<th>Description of transformer</th>
<th>Year of constr.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>single-phase 50 Hz 50/0.5 kV 0.5 MVA</td>
<td>1991</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>3-phase 50 Hz 37.5±11×0.5/13 kV 10 MVA</td>
<td>-</td>
</tr>
<tr>
<td>3</td>
<td>1</td>
<td>3-phase 50 Hz 65/6 kV 15 MVA</td>
<td>-</td>
</tr>
<tr>
<td>4</td>
<td>7</td>
<td>single-phase 50 Hz 86.6/23.2+31×0.5/16.8-8.4 kV 16.7/16.7/5.6 MVA</td>
<td>1955</td>
</tr>
<tr>
<td>5</td>
<td>6</td>
<td>single-phase 50 Hz 146.6±4/10.5 kV 21.3 MVA</td>
<td>1962</td>
</tr>
<tr>
<td>6</td>
<td>1</td>
<td>3-phase 50 Hz 155-89.5/135±16×2.3/19.5±10×0.4 kV 25 MVA</td>
<td>1955</td>
</tr>
<tr>
<td>7</td>
<td>1</td>
<td>3-phase 50 Hz 131.4±11×1.6/12.8-6.4 kV 31.5 MVA</td>
<td>1988</td>
</tr>
<tr>
<td>8</td>
<td>1</td>
<td>3-phase 50 Hz 132±11×1.8/55/16.5 kV 63/63/21 MVA</td>
<td>1985</td>
</tr>
<tr>
<td>9</td>
<td>1</td>
<td>3-phase 50 Hz 250±11×3/65 kV 185 MVA</td>
<td>1972</td>
</tr>
<tr>
<td>10</td>
<td>3</td>
<td>3-phase 50 Hz 410±2×10.3/17.5 kV 700 MVA</td>
<td>1973-76</td>
</tr>
</tbody>
</table>
5 Instrumentation and test set-up

In this chapter the instrumentation used for measurement of various dielectric responses are listed. Described are also the test set-ups used for laboratory investigations.

5.1 Instrumentation

The relaxation current measurements have been performed with a Keithley 617 electrometer. A stabilized high voltage DC source was switched to the test cell or a transformer by means of a HV relay immediately before recording the polarization current and afterwards the test object was short-circuited by another HV relay. All instruments were computer controlled. The current registration was carried out 1 s after voltage application to the test object or 1 s after its short-circuiting. For on-site measurements (power transformer), in addition, a low pass filter was used to eliminate electrical noise produced by nearby high voltage lines.

The laboratory measurements in the frequency domain have been performed with a dielectric spectrometer manufactured by Dielectric Instrumentation [Pugh, 1984].

C-tanδ measurements at 50 Hz were performed with a Tettex automatic bridge Type 2876 in the laboratory and a Tettex manual bridge Type 2805 in the field.

For recovery voltage and "polarization spectrum" measurements, a Tettex Recovery Voltage Meter was used [Tettex Instruments AG, 1992].

The oil conductivity measurement with the "triangular wave method" [Gäfvert et al., 1986] was performed with a function generator, a Keithley 617 electrometer and a digital oscilloscope.

5.2 Test set-up

The laboratory measurements on pressboard samples have been made with parallel-plate test cells with stainless steel electrodes (diameter of guarded electrodes: 113 mm). Each electrode arrangement was contained in an oil-filled glass vessel which is placed in a grounded metallic oven to control the temperature. The test cells permit placing either impregnated samples directly between the electrodes or building up a multi-layer arrangement with pressboard samples and oil ducts in series (see figure 10).

The measurements on oil samples were carried out in cells as described above, but also in a Tettex cell type 2903. To control the temperature in the Tettex cell, a thermostatic bath (LAUDA compact thermostat KS 6) was used (see figure 11).
Figure 10: Test cells used for investigations in the laboratory.

Figure 11: Tettex oil-cell combined with a thermostatic bath.
6 Measurements performed on test objects

In this chapter, the quantities measured on each group of test objects are listed and additional details concerning setting parameters and general measurement conditions are given.

6.1 Measurements on laboratory samples

In the laboratory, the following quantities were measured on pressboard, oil and multi-layer samples in dependence on temperature:

- $C\tan\delta$ at 50 Hz,
- complex capacitance,
- relaxation currents.

To avoid the superposition of dielectric responses of samples investigated, the measurements were performed with sufficiently long rest periods between the DC voltage excitations (at least 10 times longer than the previous charging duration).

6.1.1 Pressboard samples

The measurements on 2 mm thin pressboard samples have been made in cells described in section 5.2 (see figure 10). For each measurement, the samples were positioned between parallel-plate electrodes with a pressure of 0.89 N/cm$^2$. The temperature during the measurement was 20 °C. The samples were measured in the oils in which they were normally stored (first series of prepared samples by Weidmann), otherwise in new dried and degassed oils.

The $C\tan\delta$ measurements at 50 Hz were performed applying voltages up to 2'000 V$_{\text{rms}}$.

The complex capacitance was measured with the dielectric spectrometer (section 5.1), the maximum output voltage of which is 3 V$_{\text{rms}}$. The frequency range of the measurements was $1\times10^4$ Hz down to $3.16\times10^4$ Hz.

To avoid non-linear effects, the relaxation currents have been monitored with a field strength of 100 V/mm. Long time measurements for the determination of the dielectric response function have been performed with a charging duration of 200'000 s. The depolarization currents have also been measured for the same duration.

Temperature dependent quantities have been quantified for 5 °C, 20 °C, 35 °C and 50 °C. In this case, the charging duration for the measurement of relaxation currents was limited to 20'000 s.
6.1.2 Oil samples

The measurements on oil samples were carried out in cells described in section 5.2. The measurements as listed in section 6.1 were done with excitation voltages as low as possible.

Additionally, the conductivity of oil was also measured using the "triangular wave method" [Gäfvert et al., 1986], applying a 0.02 Hz triangular voltage wave of 15 Vpp. To determine the activation energy of conductivity, the temperatures during the measurements were varied from 10 °C to 90 °C.

6.1.3 Oil-paper multi-layer samples

The investigation on multi-layer samples were carried out on 3-layer arrangements in which two 2 mm pressboard disks were placed on the surface of parallel-plate electrodes and separated by a central oil duct of 4 mm or 16 mm thickness (see figure 9). For this investigation, the used oil and pressboard samples belonged always to the same "systems", which were conserved together in the same vessel.

The complex capacitance was measured with the same setting parameters as those for pressboard samples.

The C-tanδ measurements at 50 Hz were performed with a maximal voltage of 400 Vrms.

The relaxation currents were measured with voltage to electrode spacing ratios of 2 V/mm to 4 V/mm and the charging duration was limited to a maximum value of 5'000 s.

6.2 Measurements on power transformers

On power transformers, the following quantities were measured in the test laboratory of the manufacturer and in the field:

- C-tanδ at 50 Hz,
- relaxation currents,
- recovery voltage and "polarization spectrum".

Taking just one phase of a simple transformer with two windings into consideration, the measurement of relaxation currents and C-tanδ were performed by applying the excitation voltages to the high voltage winding with current sensing between the low voltage winding and the earth. In general, the low voltage winding is nearest to the limb of the core and encased by the high voltage winding. The investigated insulation in these measurements was the main duct (main insulation) between the windings. For measurement of recovery voltages or the "polarization spectrum" with a Tettex RV-meter, the DC voltage was applied
to the low voltage winding and the high voltage winding was grounded. The measurement of recovery voltage is principally performed from the HV connection of the RV-meter, this means that the insulations investigated are the main insulation between the low and high voltage windings, the insulation between the low voltage winding and the core and the insulation of the low voltage bushings. During the measurements of the above quantities the tanks and consequently the cores of transformers were always grounded. To obtain an instantaneous uniform potential distribution over the windings, it was important to join all the terminals of the high voltage windings and separately of all low voltage windings.

The voltages applied in measurements of the above quantities on transformers were chosen as low as possible to avoid the non-linear effects (see section 7.4.1). The present investigations have demonstrated that new transformers are more sensitive to non-linear effects than the old ones due to the low conductivity of their oils. For on-site investigations on new transformers, it was possible most of the time to find an adequate voltage level (below 1'000 V) for having an optimum signal to noise ratio while remaining in the linear domain. The maximal charging duration used for measurement of relaxation currents was 5'000 s.

During these measurements, particular attention was paid to attaining thermal equilibrium in the transformers investigated. An accurate determination of the temperature of the main insulation of the transformers presents a practical problem. In general, the values of the oil temperature given by the temperature sensors installed in the transformer tanks were taken into account. It is obvious that these values, depending on the position of sensors in the tank and on the accuracy of the instrumentation used, can differ somewhat from the "real" temperature values of the insulations investigated.
7 Results of investigations and discussion

The results obtained with test objects such as pressboard, oil, multi-layer oil-paper arrangements and power transformers are presented and discussed in the following four sections 7.1 to 7.4. Examples of application of the models already introduced in sections 3.9 to 3.11 are also presented. In the last section 7.5 of this chapter some additional notes concerning the procedures used for evaluation and modelling of experimental results are given.

7.1 Results obtained with pressboard samples

Two sets of pressboard samples have been analysed. The first set of new samples with various moisture content, some of which have been artificially aged, was prepared in the central laboratory of Weidmann AG. A second set of new samples was treated in the ETHZ laboratory (see section 4.1.1). The reason for preparing this second set was to investigate the transient behaviour of samples due to internal moisture distribution, to control the absolute values of quantities measured on Weidmann samples, and to understand the cause of unexpected scatter of quantities measured on samples for which an equal moisture content was assumed.

Figure 12 presents long time measurements of polarization and depolarization currents on unaged Weidmann samples. A charging voltage \( U_c \) of 200 V for a duration \( T_c \) of 200'000 s was applied for the measurement of polarization currents. The depolarization currents have been monitored for the same duration. The results show that the relaxation currents are very sensitive to the increase of moisture and that the amplitudes of their DC components vary over several decades. Pressboard with 5.0% moisture content exhibits a remarkable behaviour: For times greater than about 30'000 s there is only a weak further decrease of the depolarization current. This behaviour may be explained by a "battery effect" comprising an activation of electrochemical processes generating a persistent current in the sample. This effect appears only for samples with high moisture contents (see also figure 15) and is enhanced by longer charging duration. In addition, for this sample, even a slight increase of the polarization current after long time was observed.

Figure 13 shows the relaxation currents of artificially aged samples (see section 4.1.1), the original moisture contents of which were 0.2% and 1.0% but increased during ageing to 0.5% and 2.0%, respectively. For comparison, relaxation currents of unaged samples, whose moisture contents were quite similar to the original ones of the aged samples, are also provided in this figure.
Figure 12: Relaxation currents of Weidmann unaged pressboard samples with different moisture contents.

Figure 13: Relaxation currents of Weidmann pressboard samples before and after ageing.
The current amplitudes of aged samples are remarkably higher in the first three decades of time in comparison to those of unaged ones. Furthermore, the relaxation currents of pressboard with initially low moisture content are less affected by the ageing process than those of the sample with a high one. In general, the DC conductivity of pressboard is more influenced by moisture content than by the other ageing products [Németh, 1997]. This behaviour can well be seen by comparing the relaxation currents of new pressboard with 0.2% moisture content with those of aged pressboard with 0.5% moisture content.

Figure 14 shows the amplitude scatter of polarization currents measured on unaged Weidmann samples with moisture contents of 1.0% and 2.5%. The results refer to eleven samples for each moisture level. Some of the samples have been measured twice, that means for a short charging duration of 3'000 s as well as for a long one of 200'000 s. A direct comparison with the particular results as already presented in figures 12 and 13 discloses the fact that there only the results of samples with the highest current amplitudes and with long charging duration have been presented. As already described in section 4.1.1 in more detail, for each moisture level the moistening procedure was performed concurrently on several samples, but with checking the weight increase of just one of them. Excluding the possibility that the moisture content of individual samples did not change equally during or after impregnation, it can be assumed that the real reason for the scatter was already caused during the collective moistening process. Although not shown here in detail, it was ascertained that the scatter of results for "dry" samples of 0.2% moisture content and for aged samples of 0.5% and 2.0% was less than that of samples presented in figure 14. It is obvious that the preparation of equal "dry" samples presents no special difficulties. The lower scatter of results for aged samples can be attributed to the more homogeneous distribution of moisture and ageing products in all samples, as the ageing process was performed within closed systems and at high temperatures (see section 4.1.1).

Figure 15 shows the relaxation currents of samples as prepared in the ETHZ laboratory (ETHZ samples) for moisture contents of 1.0% and higher (see section 4.1.1). Only the result of a sample with 0.2% moisture was taken from a Weidmann "dry" sample. Once more, the "battery effect" and the slight increase of polarization currents at long time for samples with high moisture contents can be detected.

Figures 16 and 17 show a comparison between Weidmann and ETHZ sets of samples. Although a rather big quantitative difference of current amplitudes between Weidmann and ETHZ samples with presumably the same moisture content is noticeable, the general tendency of these samples with increase of moisture content is the same.

Results of measurements on ETHZ samples have shown that the relaxation currents of samples with equal moisture content and prepared with equal moisture setting procedure have less scatter than those of Weidmann samples with presumably equal moisture content. From this fact it can be concluded that the
scatter can be minimized by an improved setting of moisture content under carefully controlled conditions.

Figure 14: Scatter of relaxation current measurements for different pressboard samples with the same moisture content.

Figure 15: Relaxation currents of ETHZ unaged samples with different moisture contents.
Figure 16: Comparison between polarization currents of ETHZ and Weidmann pressboard samples.

Figure 17: Comparison between depolarization currents of ETHZ and Weidmann pressboard samples.
7.1.1 Transient behaviour of samples due to non-homogeneous moisture distribution

The results as shown in figures 12 to 17 can be assumed to be related to the influence of moisture distribution within the pressboard samples. To confirm or to disprove this assumption, two samples with 2.5% moisture content have been prepared. The samples, first of all dried under vacuum for 24 hours at 105 °C, have afterwards been exposed to ambient air with 60% relative humidity at 20 °C. The moisture absorption was continuously checked by weighing. As soon as the desired moisture level was reached, a sample "a" was immediately oil-impregnated under ambient air pressure, whereas sample "b" was stored and hermetically sealed for one week before impregnation. With this procedure, the moisture distribution within the sample "b" becomes obviously more uniform due to the diffusion of humidity, whereas the moisture content of sample "a" will be higher at the surface than inside.

In figure 18, first of all two measurements of relaxation currents on sample "a" are presented. The result "a1" was taken after 30 days of impregnation and "a2" after 90 days. The DC components of the relaxation currents as well as their initial slopes and amplitudes are markedly different. The result "b1" for sample "b" was also taken after 30 days of impregnation. The differences to result "a2", however, are not very significant, but indicate a more homogeneous moisture distribution.

![Figure 18: Relaxation currents of 2 mm pressboard samples with 2.5% moisture content, prepared with different moisture distribution. For description of samples and relaxation currents see text.](image-url)
This improved distribution was evidently brought about by the preparation procedure as explained before. Therefore, all investigations concerning the influence of moisture content have been made with this procedure (one week storage before impregnation). Additional measurements performed much later on sample "b" have confirmed its steady-state condition.

7.1.2 **Influence of charging duration on relaxation currents**

For a perfect quantification of dielectric properties of pressboard, it is necessary to measure relaxation currents with very long charging duration. This permits to make a good approximation of DC conductivity and of the dielectric response function f(t) for an extended time range from experimental data. Figure 19 shows the relaxation currents of a "dry" sample (moisture content: 0.2%) in dependence on charging duration. The currents are recorded applying a charging voltage of 200 V for charging durations of 100 s, 1'500 s, 5'000 s, 20'000 s and 200'000 s. The good consistency of polarization currents is due to the sufficiently long short circuit intervals between the successive measurements. A comparison of the depolarization currents belonging to the 20'000 s and 200'000 s charging duration shows that the increase of charging duration, even in this large time range, has still a remarkable influence upon the amplitude of depolarization currents at short times. It is obvious that this behaviour, which is especially typical for "dry" samples (see section 7.1.3), can not be simulated with a simple linear equivalent circuit (see section 7.1.6).

![Figure 19: Relaxation currents of a "dry" pressboard sample as a function of charging duration.](image-url)
7.1.3 Linearity of properties of pressboard samples

The application of classical dielectric response theory as described in section 3 will need a test to check the linearity of the samples investigated. Figure 20 shows the result of this test on a "dry" sample for which the charging voltage was changed in steps of a factor of 2, beginning with 500 V. The charging duration was 2'000 s. The linearity is confirmed by the quasi equidistant amplitudes of the relaxation currents plotted on a logarithmic scale. The present investigations have demonstrated that the limit of linearity of pressboard samples is higher than that of multi-layer samples (pressboard disks in series with oil ducts). In general, all investigations on pressboard samples in this work have been performed with an applied DC voltage below 500 V, for which the samples had a quasi linear behaviour. For some few samples with low moisture content (new samples with 0.2% and aged ones with 0.5% moisture content) a crossing over of polarization and depolarization currents was observed (see figure 13). This effect can be attributed to the injection of space charges into the sample during the charging process as also observed in other dielectric materials [Jonscher, 1983]. The non-linear behaviour of the "dry" sample of the previous section 7.1.2 can be explained in the same manner.

![Figure 20: Relaxation currents of a "dry" pressboard sample as a function of charging voltage.](image-url)
7.1.4 DC conductivity

The DC conductivities $\sigma_0$ of samples investigated are determined from relaxation currents with long charging duration (see figures 12, 13 and 15) using the relation (27) (see section 3.7). The DC conductivity values as evaluated with this method are presented in table 3.

7.1.5 C-tan$\delta$ at 50 Hz

The C-tan$\delta$ values of samples investigated have been measured at 50 Hz applying a voltage up to 2'000 $V_{\text{rms}}$. The values of C-tan$\delta$ measured on all pressboard samples investigated were not dependent on the applied voltage. Taking into account that the geometrical capacitance of samples measured was about 44.4 pF (diameter of measuring electrode: 113 mm, thickness of pressboard samples: $\approx$ 2 mm), the evaluated data of relative permittivity $\varepsilon_r$ and measured values for tan$\delta$ at 20 °C are also provided in table 3.

Table 3: DC conductivity $\sigma_0$, relative permittivity $\varepsilon_r$ and tan$\delta$ measured on pressboard samples at 20 °C.

<table>
<thead>
<tr>
<th>Sample</th>
<th>$\sigma_0$ [S/m]</th>
<th>$\varepsilon_r$ (50 Hz)</th>
<th>tan$\delta$ (50 Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weidmann (unaged, m. c.: 0.2%)</td>
<td>$1.39 \times 10^{-16}$</td>
<td>4.1</td>
<td>0.00463</td>
</tr>
<tr>
<td>Weidmann (unaged, m. c.: 1.0%)</td>
<td>$1.18 \times 10^{-15}$</td>
<td>4.3</td>
<td>0.00609</td>
</tr>
<tr>
<td>Weidmann (unaged, m. c.: 2.5%)</td>
<td>$3.36 \times 10^{-15}$</td>
<td>4.5</td>
<td>0.0055</td>
</tr>
<tr>
<td>Weidmann (unaged, m. c.: 5.0%)</td>
<td>$5.99 \times 10^{-14}$</td>
<td>4.9</td>
<td>0.0067</td>
</tr>
<tr>
<td>Weidmann (aged, m. c.: 0.5%)</td>
<td>$1.73 \times 10^{-16}$</td>
<td>4.1</td>
<td>0.00576</td>
</tr>
<tr>
<td>Weidmann (aged, m. c.: 2.0%)</td>
<td>$2.46 \times 10^{-14}$</td>
<td>4.5</td>
<td>0.0058</td>
</tr>
<tr>
<td>ETHZ (unaged, m. c.: 1.0%)</td>
<td>$1.09 \times 10^{-15}$</td>
<td>4.5</td>
<td>0.00646</td>
</tr>
<tr>
<td>ETHZ (unaged, m. c.: 2.5%)</td>
<td>$1.33 \times 10^{-14}$</td>
<td>4.8</td>
<td>0.00632</td>
</tr>
<tr>
<td>ETHZ (unaged, m. c.: 4.0%)</td>
<td>$3.21 \times 10^{-13}$</td>
<td>5.1</td>
<td>0.00937</td>
</tr>
<tr>
<td>ETHZ (unaged, m. c.: 4.9%)</td>
<td>$9.12 \times 10^{-13}$</td>
<td>5.3</td>
<td>0.01271</td>
</tr>
</tbody>
</table>
7.1.6 Modelling of pressboard samples by means of equivalent circuits

As already shown in section 3.9, the dielectric response of samples investigated in the time or frequency domain can be calculated from equivalent circuits. In this section and the next two sections, the results of dielectric responses calculated from equivalent circuits of a Weidmann "dry" sample (m. c.: 0.2%) and ETHZ samples of 1.0% and 2.5% moisture content are presented. The elements of these equivalent circuits are determined from measured relaxation currents. In the left part of table 4 the time constants $\tau_i$ and the amplitudes $A_i$ are presented, which are then used in equation (31) for fitting the depolarization current of the ETHZ pressboard sample with 1.0% moisture content (see figure 15). The calculated values of $R_j$ and $Q$ are also presented in table 4. The algorithm to determine these values is described in section 3.9. These values have been determined in the first step of iteration. This means that for the initially chosen time constants $\tau_i$, as presented in table 4, all calculated coefficients $A_i$ were positive. The result of this curve fitting (fitted curve 1) is shown in figure 21. In the right part of table 4, the values of the elements of an equivalent circuit with an expanded number of RC series combinations are given. These values have been determined from the measured depolarization current, but extrapolated for two decades down to 0.01 s. A simple linear extrapolation in a double logarithmic plot was used to determine the current values for times less than 1 s. In figure 21, the results of this extrapolation and this second curve fitting (fitted curve 2) are shown. The aim of this extrapolation will be explained in section 7.1.7. The values of the elements $R_0$ and $C_{50 \text{ Hz}}$ are determined from the relative permittivity of 4.5 and the DC conductivity of $1.09 \times 10^{-15}$ S/m of this sample (see table 3). The values of $R_0$ and $C_{50 \text{ Hz}}$ are 182.25 TΩ and 201 pF, respectively. The accuracy of these fits can be quantified with the largest values for the relative difference between measured and fitted curves. These values for the first and second fitting are 0.68% and 0.2%, respectively, and are well within the measuring uncertainty.

Figure 22 shows the comparison between depolarization currents measured with short charging duration on samples with moisture contents of 0.2%, 1.0% and 2.5% and currents calculated from their equivalent circuits (full lines) determined from depolarization currents belonging to a 200'000 s charging duration (see figure 15). At long times, the current values calculated for pressboard with 2.5% moisture content are somewhat higher than the measured ones. This is due to the fact that the equivalent circuit of this sample, determined from depolarization current belonging to a 200'000 s charging duration, takes also the persistent current due to the "battery effect" (see figure 15) into account; it delivers, therefore at long times higher current values for shorter charging durations. The somewhat higher amplitudes of the calculated depolarization currents of the sample with 0.2% moisture content are due to the non-linear behaviour of this sample as presented in section 7.1.2 (see figure 19). Therefore, for this sample, the amplitudes of currents calculated for charging durations of less than 200'000 s will be higher than the measured ones. In the same figure are also presented, with
dashed lines, the current curves calculated from the polarization currents belonging to a 200'000 s charging duration (see figure 15), according to equations (21) and (52).

Table 4: Parameters of curve fitting and values of elements of equivalent circuits of a ETHZ sample with 1.0% moisture content. For more explanation see text.

<table>
<thead>
<tr>
<th></th>
<th>1) Without extrapolation</th>
<th>2) With extrapolation</th>
</tr>
</thead>
<tbody>
<tr>
<td>i</td>
<td>A_i [A]</td>
<td>τ_i [s]</td>
</tr>
<tr>
<td>1</td>
<td>4.00×10^{-10}</td>
<td>0.3162</td>
</tr>
<tr>
<td>2</td>
<td>2.16×10^{-10}</td>
<td>1</td>
</tr>
<tr>
<td>3</td>
<td>6.63×10^{-11}</td>
<td>3.162</td>
</tr>
<tr>
<td>4</td>
<td>2.21×10^{-11}</td>
<td>10</td>
</tr>
<tr>
<td>5</td>
<td>1.11×10^{-11}</td>
<td>31.62</td>
</tr>
<tr>
<td>6</td>
<td>5.77×10^{-12}</td>
<td>100</td>
</tr>
<tr>
<td>7</td>
<td>4.22×10^{-12}</td>
<td>316.2</td>
</tr>
<tr>
<td>8</td>
<td>3.34×10^{-12}</td>
<td>1'000</td>
</tr>
<tr>
<td>9</td>
<td>2.15×10^{-12}</td>
<td>3'162</td>
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<tr>
<td>10</td>
<td>1.26×10^{-12}</td>
<td>10'000</td>
</tr>
<tr>
<td>11</td>
<td>6.87×10^{-13}</td>
<td>31'620</td>
</tr>
<tr>
<td>12</td>
<td>1.72×10^{-13}</td>
<td>100'000</td>
</tr>
<tr>
<td>13</td>
<td>1.23×10^{-13}</td>
<td>316'200</td>
</tr>
</tbody>
</table>
Figure 21: Comparison of measured and extrapolated depolarization current values of a pressboard sample with 1.0% moisture content to their fitted curves.

Figure 22: Comparison of measured depolarization currents with calculated ones, obtained from the equivalent circuits (full lines) and from the polarization currents (dashed lines). For more explanation see text.
7.1.7 Complex capacitance $C(\omega)$ and $\tan\delta(\omega)$

The complex capacitance $C(\omega)$ and $\tan\delta(\omega)$ have been measured with the dielectric spectrometer for the frequency range of $3.16 \times 10^4 \text{ Hz}$ to $1 \times 10^4 \text{ Hz}$, applying an excitation voltage of $3 \text{ V}_{\text{rms}}$. Figures 23 and 24 display the values measured for the real part of capacitance $C'(\omega)$ and $\tan\delta(\omega)$ for Weidmann samples. In figures 25 and 26, the results of measurements on ETHZ samples are presented, together with the results of the "dry" Weidmann sample of 0.2% moisture content as already shown in figures 23 and 24.

By means of the equivalent circuits of investigated samples already established, their complex capacitances are easily determined from their frequency responses. In figures 27, 28 and 29, the measured values of complex capacitance (real and imaginary part) as well as the measured $\tan\delta$ values are compared for a Weidmann "dry" sample and ETHZ samples with 1.0% and 2.5% moisture content with calculated curves as determined from the frequency response of the corresponding equivalent circuits. A relatively significant difference between calculated and measured values of $C''$ and consequently of $\tan\delta$ at low frequencies for the sample with 0.2% moisture content is evident. This lack of coincidence has always been observed with "dry" samples with low moisture content. Obviously, the deviation of measured from calculated values of samples presented at "high" frequencies ($>0.1 \text{ Hz}$) is due to the limited high frequency information as obtained from relaxation current measurements commencing only after 1 s. The values at high frequencies can be approximated, extrapolating the measured relaxation currents to short times. The dashed curves are calculated from equivalent circuits determined from relaxation currents, which are extrapolated over two decades to short times (see section 7.1.6). To show the influence of DC conductivity on the simulated curves of $C''(\omega)$ and $\tan\delta(\omega)$, additional simulations (thin lines) are shown for a sample of 0.2% moisture content with two new conductivity values, which are three and six times larger than the initially determined value of $\sigma_0 = 1.39 \times 10^{-16} \text{ S/m}$. 
Figure 23: Real part of the complex capacitance of Weidmann pressboard samples in dependence on frequency.

Figure 24: \( \tan \delta \) of Weidmann pressboard samples in dependence on frequency.
Figure 25: Real part of the complex capacitance of ETHZ pressboard samples in dependence on frequency.

Figure 26: tanδ of ETHZ pressboard samples in dependence on frequency.
Figure 27: Measured and calculated values of the real part of the complex capacitance of pressboard samples with 0.2%, 1.0% and 2.5% moisture content.

Figure 28: Measured and calculated values of the imaginary part of the complex capacitance of pressboard samples with 0.2%, 1.0% and 2.5% moisture content.
Figure 29: Measured and calculated values of the tanδ of pressboard samples with 0.2%, 1.0% and 2.5% moisture content.
7.1.8 Recovery voltage and "polarization spectrum"

The recovery voltages for different charging and short circuit durations as well as the derived "polarization spectra" of pressboard samples can also be calculated from the equivalent circuit (see sections 3.5 and 3.9). Figure 30 shows the recovery voltages calculated for a Weidmann "dry" sample and ETHZ samples with 1.0% and 2.5% moisture content, for a charging voltage of 1 V and charging durations of 100 s and 1'000 s. The ratio of charging to short-circuit duration was 2. Presented are also the recovery voltage curves for the "dry" sample, but with higher values of conductivities as already mentioned in section 7.1.7. The initial slope $S_{r0}$, the position in time of maximum $t_{r \text{max}}$ and the maximum value $V_{r \text{max}}$ of recovery voltages are presented in table 5.

Figure 31 displays the calculated "polarization spectra" of the modelled samples for a charging voltage of 1 V and a charging to discharging ratio of 2. The charging duration is varied from 2 s to 10'000 s (see section 3.5). The maximum of the "polarization spectrum" for the sample with 2.5% moisture content is located at 2'300 s and its value is equal to 0.13 V. All other maxima appear at times larger than 10'000 s. Due to the relatively small capacitance of the investigated pressboard samples (circa 200 pF), the measurement of a "polarization spectrum" on these laboratory samples with the Tettex RV-meter was not possible. Therefore, the comparison between measured and calculated "polarization spectra" had to be carried out on power transformers, as discussed in section 7.4.

![Figure 30: Calculated recovery voltages of pressboard samples with 0.2%, 1.0% and 2.5% moisture content.](image-url)
Table 5: The initial slope $S_{r0}$, the position in time of maximum $t_{r_{\text{max}}}$ and the maximum value $V_{r_{\text{max}}}$ of simulated recovery voltages as presented in figure 30.

<table>
<thead>
<tr>
<th>Sample</th>
<th>$S_{r0}$ [V/s]</th>
<th>$t_{r_{\text{max}}}$ [s]</th>
<th>$V_{r_{\text{max}}}$ [mV]</th>
<th>$S_{r0}$ [V/s]</th>
<th>$t_{r_{\text{max}}}$ [s]</th>
<th>$V_{r_{\text{max}}}$ [mV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>unaged, m. c.: 0.2%</td>
<td>$4.22 \times 10^{-5}$</td>
<td>9'079.9</td>
<td>5.34</td>
<td>$1.28 \times 10^{-5}$</td>
<td>21'286</td>
<td>19.1</td>
</tr>
<tr>
<td>$\sigma_0 = 1.39 \times 10^{-16}$ S/m</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>unaged, m. c.: 0.2%</td>
<td>$4.22 \times 10^{-5}$</td>
<td>5'998.7</td>
<td>5.11</td>
<td>$1.28 \times 10^{-5}$</td>
<td>14'813</td>
<td>17.4</td>
</tr>
<tr>
<td>$\sigma_1 = 3 \times \sigma_0$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>unaged, m. c.: 0.2%</td>
<td>$4.22 \times 10^{-5}$</td>
<td>4'178.7</td>
<td>4.88</td>
<td>$1.28 \times 10^{-5}$</td>
<td>11'045</td>
<td>15.8</td>
</tr>
<tr>
<td>$\sigma_2 = 6 \times \sigma_0$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>unaged, m. c.: 1.0%</td>
<td>$14.69 \times 10^{-5}$</td>
<td>1'929.8</td>
<td>18.03</td>
<td>$6.93 \times 10^{-5}$</td>
<td>5'243.6</td>
<td>52.00</td>
</tr>
<tr>
<td>unaged, m. c.: 2.5%</td>
<td>$98.09 \times 10^{-5}$</td>
<td>413.4</td>
<td>64.75</td>
<td>$47.23 \times 10^{-5}$</td>
<td>1526.7</td>
<td>122.86</td>
</tr>
</tbody>
</table>

Figure 31: Calculated "polarization spectra" of pressboard samples with 0.2%, 1.0% and 2.5% moisture content.
7.1.9 Temperature-dependent behaviour of pressboard material

To study the temperature behaviour of the present samples, the dielectric responses in the time and frequency domains have been measured at 5 °C, 20 °C, 35 °C and 50 °C. As already mentioned in section 3.8, the temperature dependence of the DC conductivity of pressboard obeyed a quasi-exponential law. Therefore, it can be characterized by an activation energy. The temperature behaviour of dielectric loss can be deduced from a shift necessary to form a "master curve" of susceptibility (real or imaginary part) in the frequency domain, or a "master curve" of dielectric response function or depolarization current, for long charging duration, in the time domain (see section 3.8). In case of impregnated pressboard this shift obeyed an exponential law and can consequently be characterized by an activation energy.

Figure 32 shows the imaginary part of the complex capacitance $C''(\omega)$ (dashed lines) of an ETHZ pressboard sample with 2.5% moisture content at 5 °C, 20 °C, 35 °C and 50 °C, as measured with the dielectric spectrometer. The continuous lines represent the term $C_0\chi''(\omega)$, which can be calculated from $C''(\omega)$ by subtracting the DC contribution (see equations (14) and (24)). Figure 33 shows the "master curve" of $C_0\chi''(\omega)$ at 20 °C as formed from the shift of former presented spectra along the frequency axis.

Figure 34 presents the relaxation currents of the same sample in dependence on temperature. The measurements are performed applying 500 V for a duration of 20'000 s. According to the theory of Fourier transforms, a horizontal shift in the frequency domain corresponds to a shift along a line with a slope of -1 in the double logarithmic plot in the time domain. Figure 35 shows now the "master curve" of depolarization current of this sample at 20 °C. To minimize the influence of limited charging duration, new depolarization currents with a hypothetical infinite charging duration have been calculated from equivalent circuits as derived from measured depolarization currents in figure 34 and only the initial values up to 2'000 s have been shifted along the line with slope of -1 until coincidence was attained.

Finally, figure 36 presents the Arrhenius plot of the logarithmic shift for this sample. According to equation (29), the activation energy of the loss can be calculated from the slope of the fitted line and is here equal to 1.07 eV. The present investigations have shown that both activation energies of DC conductivity $E_{ac}$ and loss $E_{al}$ are slightly augmented by the increase of moisture content. Table 6 groups the values of $E_{ac}$ and $E_{al}$, which have been determined from measurements of dependence on temperature on a significant number of the present samples.
Figure 32: Loss part (with and without DC contribution) of a pressboard sample with 2.5% moisture content measured at different temperatures.

Figure 33: Loss "Master curve" of a pressboard sample with 2.5% moisture content at 20 °C, derived from the curves in figure 32.
Figure 34: Relaxation currents of a pressboard sample with 2.5% moisture content measured at different temperatures.

Figure 35: "Master curve" of depolarization current, obtained from shifting the depolarization current curves (figure 34) measured at different temperatures, as described in the text.
Figure 36: Logarithmic shift as a function of temperature: Arrhenius plot.

Table 6: Activation energies of DC conductivity $E_{ac}$ and loss $E_{al}$ measured on pressboard samples.

<table>
<thead>
<tr>
<th>Sample</th>
<th>$E_{ac}$ [eV]</th>
<th>$E_{al}$ [eV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weidmann (unaged, m. c.: 0.2%)</td>
<td>0.9</td>
<td>0.86</td>
</tr>
<tr>
<td>Weidmann (unaged, m. c.: 1.0%)</td>
<td>0.96</td>
<td>1.18</td>
</tr>
<tr>
<td>Weidmann (unaged, m. c.: 5.0%)</td>
<td>1.15</td>
<td>1.06</td>
</tr>
<tr>
<td>Weidmann (aged, m. c.: 0.5%)</td>
<td>1.11</td>
<td>1.02</td>
</tr>
<tr>
<td>Weidmann (aged, m. c.: 2.0%)</td>
<td>0.92</td>
<td>1.08</td>
</tr>
<tr>
<td>ETHZ (unaged, m. c.: 1.0%)</td>
<td>0.94</td>
<td>1.09</td>
</tr>
<tr>
<td>ETHZ (unaged, m. c.: 2.5%)</td>
<td>1.11</td>
<td>1.07</td>
</tr>
<tr>
<td>ETHZ (unaged, m. c.: 4.0%)</td>
<td>1.09</td>
<td>1.16</td>
</tr>
</tbody>
</table>
7.2 Results obtained with oil samples

Present measurements of dielectric response on oil samples have demonstrated that dielectric dispersion within the frequency range of interest, i.e. for frequencies approximately equal to or lower than power frequency can be neglected. This means that in the time domain the dielectric response function \( f(t) \) for times higher than 1 s can be taken as zero. Therefore, for the investigations in this work the oil is characterized by its relative permittivity at power frequency (about 2.2), its conductivity and its activation energy, which describes the temperature dependence of conductivity. The relative permittivity of oil at power frequency decreases with increasing temperature. For temperatures above 0 °C, this decrease is mainly due to the volume expansion of oil [von Münch, 1987; Bartnikas, 1994]. This temperature dependence can be neglected for practical application of the present models for the temperature range of 10 °C to 35 °C.

Figure 37 shows the polarization and depolarization currents of a sample of new (unused) mineral oil in dependence on increasing charging duration. The measurements are performed applying a DC voltage of 10 V to a 2 mm oil gap in a cell with parallel plate electrodes (see section 5.2). The initial high amplitudes of polarization currents and their transition to low values are due to the motion of charge carriers (ionic impurities) within the gap from their initial positions to the electrodes (charge accumulation on electrodes). It is evident that the motion velocity of these charge carriers is dependent on the amplitude of the voltage applied. This means that the transition part of the polarization current will be shifted to shorter times by increasing the excitation voltage level. The global amplitude of depolarization currents, for charging durations higher than 1'500 s, decreased after each additional period of voltage application. This is obviously due to the reduction (recombination, neutralisation) of a part of the charge carriers at the electrodes after each excitation. These responses of oil to the DC voltages applied show that the currents generated for times > 1 s are mainly due to the motion of charge carriers. Therefore, they differ fundamentally from the relaxation currents, which can be observed in solid dielectrics.

The conductivity of oil will change continuously by the application of a DC voltage (see the polarization currents in figure 37). The values determined at short times correspond to the values determined with AC or combined low voltage low frequency methods [Gäfvert et al., 1986; Tobazéon et al., 1994; Li, Rungis, 1997]. This is also verified for the sample presented here. From the measurement performed with a 0.02 Hz triangular voltage wave of 15 V\(_{pp}\), a conductivity of \(1.42\times10^{-13}\) S/m was determined. This value corresponds to a conductivity value, which can be evaluated from the polarization current after 28 s of a DC voltage application.

The temperature dependence of oil obeys a quasi-exponential law, which can be characterized by an activation energy of 0.4 to 0.5 eV. The measurements of conductivity ("triangular wave method") performed in this work in dependence
on temperature on new and used oils showed that the activation energies of used or impure oils are slightly lower than those of new and pure ones. These results are in agreement with the investigation performed by [Diabi et al., 1996].

The conductivity of oil is quite sensitive to impurities and is also influenced by high moisture content, for which the conductivity increases [Beyer et al., 1986]. This influence is, however, quite small as long as moisture is restricted to less than about 20 ppm [Itahashi et al., 1995; Washabaugh et al., 1996]. The present results of conductivity measurements ("triangular wave method") at 20 °C for several new and used oil samples, taken from the investigated transformers, are in a range of $1\times10^{-13}$ S/m to $5\times10^{-11}$ S/m.

![Figure 37: Polarization and depolarization currents of a new (unused) mineral oil in dependence on increasing charging duration.](image)

- **Figure 37**: Polarization and depolarization currents of a new (unused) mineral oil in dependence on increasing charging duration.
7.3 Results obtained with oil-paper multi-layer samples

Measurements on multi-layer arrangements, i.e. pressboard disks in series with oil gaps, a configuration which is relevant for power transformers, disclosed that the dielectric response in the time or frequency domain is not only dependent on the material condition of each component, but also on the volume ratios. The following results of relaxation current measurements are taken from samples consisting of a 3-layer arrangement, in which two 2 mm pressboard disks are placed on the surface of parallel-plate electrodes and are separated by a central oil duct of variable thickness (see figure 9). Current measurements were performed with a voltage to electrode spacing ratio of 3 V/mm, the charging duration has been limited to 5'000 s. Figure 38 shows the results of these measurements. The relaxation currents "a" to "c" are measured with an unaged system characterized by a pressboard moisture content of 0.2%. For system "a", the oil moisture content was 5 ppm and the oil conductivity was quantified to be 0.5 pS/m. The currents for system "b" have been measured after replacing the oil of the system "a" by a new one, decreasing the oil conductivity from 0.5 to 0.3 pS/m. The third measurement "c" was performed by changing the ratio of oil to pressboard from 4 to 1 (from 16 mm to 4 mm oil duct). Relaxation currents for system "d" belong to an aged system characterized by a pressboard moisture content of 2.0%, an oil moisture content of 19 ppm and an oil conductivity of 0.1 pS/m. The reason for the low conductivity of this aged oil is assumed to be due to the "purification" phenomenon caused by the preceding relaxation current measurements which had had long charging durations.

![Figure 38: Relaxation currents of different multi-layer samples.](image-url)
These results show clearly that the predominantly exponential decay of relaxation currents which is due to the interfacial polarization between oil duct and pressboard disks is essentially controlled by the change of oil conductivity and by the volume ratio of oil to pressboard. The dielectric response of the pressboard in multi-layer samples becomes mainly apparent at long times after completion of interfacial polarization and depolarization.

7.3.1 Influence of charging duration on relaxation currents

The charging duration dependence of the relaxation currents of a multi-layer arrangement is presented in figure 39. These currents have been measured on system "a" described above for charging durations of 30 s, 100 s, 300 s, 1'500 s and 5'000 s. A good consistency of polarization currents can be noticed. The initial amplitudes of the depolarization currents increase in function of charging duration. This behaviour is due to the time dependent build up of the interfacial polarization and can be derived well from the exponential time dependence of the generated currents [von Hippel, 1966; Fournie, 1986].

![Figure 39: Charging duration dependence of the relaxation currents of a multi-layer sample.](image)
7.3.2 Non-linear effects

The investigation demonstrated that multi-layer arrangements are showing more pronounced non-linear effects than simple pressboard samples. To minimize non-linear effects, the experiments have been carried out applying a voltage to electrode spacing ratio of 2 V/mm to 4 V/mm. Figure 40 shows an example of typical non-linear relaxation currents, which can be generated in multi-layer samples by applying much higher voltages. For this experiment, the investigated sample was formed from two 2 mm aged pressboard samples (moisture content: 0.5%) separated by an oil gap of 4 mm. It is obvious that the behaviour of these currents cannot be described by the linear models. Typical characteristics of the shape of these currents are: the initial low amplitude of the depolarization currents in comparison to the polarization currents, the local maxima of the depolarization currents and the relative high amplitudes of the depolarization currents at times later than these maxima. In addition, the increase of charging voltage and duration amplifies this effect and moves the local maxima to shorter times. The time dependence of these currents indicates a limitation of the interfacial depolarization immediately after the short-circuit. This phenomenon could be explained by an attachment of oil charge carriers on the surfaces of the pressboard disks due to the high local field strength during the charging process combined with a delayed detachment (movement) after the short-circuit. This effect is clearly reproducible and occurs mainly in multi-layer arrangements with low conductivity of oil.

Figure 40: Non-linear relaxation currents generated in a multi-layer sample by applying high voltages.
7.3.3 DC conductivity

The values of DC conductivity of pressboard samples were determined from relaxation currents belonging to a 200'000 s charging duration (see section 7.1.4). For multi-layer arrangements, the values of DC conductivity can also be approximated in the same way. It is, however, obvious that the values as quantified by the relatively short charging duration of 5'000 s will be less accurate. This problem can be solved by extrapolating the polarization currents to their DC regimes for long times. Table 7 groups the values of DC conductivities of the samples in figure 38, determined from the relaxation currents using equation (26), but also from the values approximated from the extrapolated polarization currents.

7.3.4 C-tanδ at 50 Hz

To avoid non-linear effects the values of C-tanδ have been measured with voltages not higher than 400 V\text{ms}. Taking into account that the geometrical capacitances of sample "a", "b" and "d" were about 4.4 pF and that of sample "c" was about 11.1 pF, the following values of relative permittivity $\varepsilon_r$ and tanδ have been measured at 20 °C (see table 7).

Table 7: DC conductivity $\sigma_0$ (see section 7.3.3), relative permittivity $\varepsilon_r$ and tanδ measured at 20 °C on multi-layer samples presented in figure 38.

<table>
<thead>
<tr>
<th>Sample</th>
<th>$\sigma_0$ [S/m]</th>
<th>$\sigma_0$ [S/m] *</th>
<th>$\varepsilon_r$ (50 Hz)</th>
<th>tanδ (50 Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>1.79x10^{-15}</td>
<td>6.87x10^{-16}</td>
<td>2.41</td>
<td>0.00065</td>
</tr>
<tr>
<td>b</td>
<td>3.06x10^{-15}</td>
<td>6.82x10^{-16}</td>
<td>2.44</td>
<td>0.00050</td>
</tr>
<tr>
<td>c</td>
<td>1.09x10^{-15}</td>
<td>2.77x10^{-16}</td>
<td>2.95</td>
<td>0.00162</td>
</tr>
<tr>
<td>d</td>
<td>7.17x10^{-14}</td>
<td>6.65x10^{-14}</td>
<td>2.45</td>
<td>0.00060</td>
</tr>
</tbody>
</table>

* Approximated from the extrapolated polarization currents.
7.3.5 Modelling of oil-paper multi-layer samples by means of equivalent circuits

The measured relaxation currents of the multi-layer samples as presented in figure 38 can again be used to quantify their associated equivalent circuits. From these circuits, other quantities such as complex capacitance, tanδ or "polarization spectrum" can easily be calculated (see sections 7.3.6 and 7.3.7). Table 8 presents the fitting parameters and the values of the elements of the equivalent circuit of sample "a", which have been determined from the depolarization currents as measured in the time interval from 1 s to 10'000 s. These values are obtained after the third iteration step of the algorithm presented in section 3.9. Twenty time constants have initially been chosen, which were distributed "equidistantly" on the logarithmic time scale between 0.56 s to 31'620 s. For this sample, the largest relative difference between the measured and fitted curves was 0.35%. The values of \(C_{50\,\text{Hz}}\) and \(R_o\) for this sample were 10.72 pF and 1'115 TΩ, respectively. The more accurate value of \(R_o\) as determined from the extrapolated polarization current was 2'902 TΩ.

In general, for an equal measuring time interval the depolarization currents of multi-layer samples can be modelled with fewer RC elements than the currents of simple pressboard samples.

Figure 41 shows the comparison between measured values and fitted curves of the depolarization currents of multi-layer samples presented in figure 38. In the same figure the calculated curves for 100 s charging duration, obtained from the corresponding equivalent circuits (full lines) and from the polarization currents (dashed lines), according to equations (21) and (52), are compared with the measured ones.

**Table 8: Parameters of curve fitting and values of elements of equivalent circuit of sample "a" (see figure 38).**

<table>
<thead>
<tr>
<th>i</th>
<th>(A_i) [A]</th>
<th>(\tau_i) [s]</th>
<th>(R_i) [TΩ]</th>
<th>(C_i) [pF]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>(4.91\times10^{-13})</td>
<td>31.62</td>
<td>122.29</td>
<td>0.26</td>
</tr>
<tr>
<td>2</td>
<td>(2.79\times10^{-12})</td>
<td>177.8</td>
<td>21.54</td>
<td>8.25</td>
</tr>
<tr>
<td>3</td>
<td>(8.77\times10^{-12})</td>
<td>316.2</td>
<td>6.84</td>
<td>46.21</td>
</tr>
<tr>
<td>4</td>
<td>(5.57\times10^{-13})</td>
<td>562.3</td>
<td>107.75</td>
<td>5.22</td>
</tr>
<tr>
<td>5</td>
<td>(1.42\times10^{-12})</td>
<td>1'000</td>
<td>41.89</td>
<td>23.87</td>
</tr>
<tr>
<td>6</td>
<td>(1.79\times10^{-13})</td>
<td>3'162</td>
<td>266.42</td>
<td>11.87</td>
</tr>
<tr>
<td>7</td>
<td>(2.80\times10^{-14})</td>
<td>10'000</td>
<td>842.46</td>
<td>11.87</td>
</tr>
</tbody>
</table>
Figure 41: Comparison between the measured values of the depolarization currents with 5'000 s charging duration and their fitted curves. Additional comparison of the depolarization currents with 100 s charging duration to calculated curves obtained from the equivalent circuits (full lines) and from the polarization currents (dashed lines). For more explanation see text.
7.3.6 Complex capacitance $C(\omega)$ and $\tan\delta(\omega)$

Figures 42, 43 and 44 show the real and imaginary part of the complex capacitance and the $\tan\delta$ of the four multi-layer samples extensively investigated here, as measured with the dielectric spectrometer. In the same figures, the calculated quantities derived from the frequency responses of the equivalent circuits are also displayed. In the figures 43 and 44 the calculated curves are also included, as obtained from the extrapolated values of conductivities (see table 7). These simulations show that for "dry" systems the decrease of conductivity (extrapolated values) will mainly influence the magnitudes of $C''$ and, consequently, the $\tan\delta$ values at low frequencies.

**Figure 42**: Measured and calculated values of the real part of the complex capacitance of different multi-layer samples. Calculation based on the equivalent circuits obtained from their relaxation currents.
Figure 43: Measured and calculated values of the imaginary part of the complex capacitance of different multi-layer samples. Calculation based on the equivalent circuits obtained from their relaxation currents.

Figure 44: Measured and calculated values of the \( \tan \delta \) of different multi-layer samples. Calculation based on the equivalent circuits obtained from their relaxation currents.
7.3.7 "Polarization spectrum"

Figure 45 shows the "polarization spectra" of the investigated samples which were calculated from the equivalent circuits. The simulations have been done for a charging voltage of 1 V. In addition, curves as calculated from equivalent circuits with extrapolated values of DC conductivities are also displayed (dashed curves). The calculated curves show clearly that the position in time of the maximum in the "polarization spectrum" corresponds to the time constant of the interfacial polarization (see the predominant exponential time dependence of the relaxation currents in figure 38). This position in time does change in function of oil conductivity and ratio of oil to pressboard. This fact is in complete contradiction to the statements and assumptions as published elsewhere [Bognar et al., 1990]. Therefore, this position in time cannot be considered as a unique criterion for the evaluation of moisture content of the pressboard in a multi-layer test object.

Table 9 groups the characteristic quantities of the "polarization spectra" as presented in figure 45. The values of pressboard moisture content are also given, as provided from the "software for analysis" (Type 5461/SWRVM2) delivered together with the RV-meter by the Tettex company.

![Figure 45](image)

**Figure 45:** Calculated "polarization spectra" of different multi-layer samples. Calculation based on the equivalent circuits obtained from their relaxation currents.
Table 9: Characteristic quantities of "polarization spectra" presented in figure 45 and erroneously estimated moisture content of pressboard which would result from application of the Tettex "software for analysis".

<table>
<thead>
<tr>
<th>Sample</th>
<th>$T_{c, \text{max}}$ [s]</th>
<th>$V_{\text{max}}$ [V]</th>
<th>Moisture content [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>351 (352) *</td>
<td>0.3002 (0.3012) *</td>
<td>1.47 (1.47) *</td>
</tr>
<tr>
<td>b</td>
<td>785 (821) *</td>
<td>0.2770 (0.2827) *</td>
<td>1.07 (1.05) *</td>
</tr>
<tr>
<td>c</td>
<td>325 (332) *</td>
<td>0.1896 (0.1917) *</td>
<td>1.51 (1.50) *</td>
</tr>
<tr>
<td>d</td>
<td>1102 (1114) *</td>
<td>0.0542 (0.0565) *</td>
<td>0.91 (0.90) *</td>
</tr>
</tbody>
</table>

* Values determined from calculated "polarization spectra" obtained from the equivalent circuits with extrapolated $\sigma_0$.

7.3.8 Modelling of oil-paper multi-layer samples by means of "extended" equivalent circuits

The relaxation currents of oil-paper multi-layer samples can be calculated according to equations (41), (42) and (43), with the knowledge of the geometric capacitances and the dielectric properties of the constituent materials. The pressboard is characterized by its power frequency relative permittivity, DC conductivity, and dielectric response function, which is obtained according to equations (20) and (21) from directly measured relaxation currents. For measuring times $>1$ s the dielectric response function of oil is negligible (see section 7.2). Therefore, oil is just characterized by its conductivity and power frequency relative permittivity. As already mentioned in section 3.10, the system of equations (41), (42) and (43) represents an "extended" equivalent circuit (see figure 5), the elements of which can also be determined from the geometric capacitances and the dielectric properties of the constituent materials.

Figure 46 shows once more the relaxation currents measured on sample "d" in figure 38 together with the calculated relaxation currents. In this calculation, the oil is characterized by its relative permittivity of 2.2 and its conductivity of 0.1 pS/m. The DC conductivity and relative permittivity values of pressboard are taken from table 3. The dielectric response function is approximated from the measured depolarization current, as presented in figure 13, by dividing the initial values up to 10'000 s (less than 1/10 of charging duration of 200'000 s) by the geometrical capacitance and applied voltage values. In figure 46, the dashed lines represent the currents generated by the interfacial polarization and depolarization only [von Hippel, 1966; Fournié, 1986]. This solution is calculated considering the pressboard as a resistive and non-dispersive material neglecting the dielectric response function in equation (43).
Figure 46: Measured and calculated relaxation currents of an aged multi-layer sample. The dashed curves represent the currents generated by the interfacial polarization and depolarization.
7.3.9 Temperature-dependent behaviour of multi-layer samples

When pressboard samples and oil ducts are combined to form a multi-layer arrangement, the temperature dependence of relaxation currents alters significantly, as the conductivity of the oil will also change with the temperature. Figure 47 presents some results for temperature-dependent currents of a multi-layer sample, built-up from two 2 mm pressboard disks (moisture content: 0.2%) separated by a central oil duct of 16 mm. The measurements have been performed at temperatures of 5 °C, 20 °C and 35 °C with a voltage to electrode spacing ratio of 3 V/mm and for a charging duration $T_c$ of 5'000 s. The initial differences in the amplitudes between polarization and depolarization currents are caused by a charging duration which is insufficient to complete the interfacial polarization. With the increase of temperature, the change in amplitudes and time dependence of the currents is mainly due to the decrease of the time constant of the interfacial polarization. The changes due to the increase of amplitudes of the DC components and due to the shift of dielectric response of pressboard appear mainly at long times.

![Figure 47: Relaxation currents of a multi-layer sample in dependence on temperature.](image)

**Figure 47**: Relaxation currents of a multi-layer sample in dependence on temperature.
7.4 Results obtained with power transformers

Investigations on new and used power transformers have demonstrated that the dielectric response of the main insulation can be described well by the linear models introduced in section 3. As already described in section 3.11 the main insulation of a power transformer can be represented by a composition of three elements, a pressboard barrier in series with an oil duct and a pressboard spacer parallel to these. Therefore the dielectric response of a power transformer will be a composition of responses, as presented in sections 7.1 and 7.3, for simple pressboard samples and for multi-layer samples.

Figure 48 presents a typical example of relaxation currents measured on two presumably identical single-phase 146.6±4/10.5 kV 21.3 MVA power transformers, manufactured in 1962. The measurements were performed on-site, applying a charging voltage of 2'000 V for a duration of 5'000 s. The oil temperatures of both transformers were 24°C. In analogy to multi-layer samples, the initially predominant exponential shape of relaxation currents is due to the exponential time dependence of interfacial polarization and depolarization currents generated from the series arrangement of the oil ducts and pressboard barriers. For long times, the dielectric response of pressboard barriers becomes more apparent with the completion of the interfacial polarization. The small contribution of the relaxation currents of spacers influences mainly the shape of currents at long times.

![Figure 48: Relaxation currents of two presumably identical used single-phase 146.6±4/10.5 kV 21.3 MVA power transformers.](image-url)
The big difference in the initial exponential region of the presented currents in figure 48 is due to the difference of oil conductivity, which is a predominant factor in the interfacial polarization (see figure 38). In fact, conductivity measurements on oil samples at 24 °C showed that the oil conductivity of transformer "a" was lower (0.9 pS/m) than that of transformer "b" (4.2 pS/m).

7.4.1 Non-linear effects

For application of linear models to measured dielectric responses, it is important to avoid non-linear effects due to high excitation voltages. The present investigations have shown that it is, in general, possible to perform measurements with sufficiently high signal to noise ratio remaining in the linear domain and this even under on-site conditions. Figure 49 presents the relaxation currents in dependence on applied charging voltages of 500 V and 2'000 V of a new 3-phase 132±11×1.6/12.2 kV 31.5 MVA power transformer as measured in the laboratory of the manufacturer. To simplify the comparison, currents as obtained with 500 V charging voltage are multiplied by a factor of 4 and presented by thin lines, too. These curves show also that in case of power transformers a non-linear effect similar to that of the multi-layer sample (see section 7.3.2) can in fact occur. This behaviour seems to be typical for new transformers with low conductivity of oil. Its origin can be explained in the same manner as for multi-layer samples (see section 7.3.2).

Figure 49: Relaxation currents showing non-linearity as measured on a new three-phase 132±11×1.6/12.2 kV 31.5 MVA power transformer.
7.4.2 Modelling of power transformers by means of equivalent circuits

As already shown in sections 7.3.5, 7.3.6 and 7.3.7 the dielectric behaviour of multi-layer samples is modelled well by the simple equivalent circuit introduced in section 3.9. The elements of the equivalent circuit of these samples can just be determined from measured relaxation currents and capacitance values and no supplementary knowledge about the composition (volume ration of oil to pressboard) is needed. In this section, the applicability of this model for "real" test object is demonstrated, that is for a single-phase 50/0.5 kV 500 kVA testing transformer, manufactured in 1991. This transformer is located in the laboratory of the ETHZ and all measurements have been performed at a constant temperature of 21 °C.

Figure 50 shows the relaxation currents of this transformer in dependence on charging duration. A charging voltage of 2'000 V was applied to the high voltage windings (outer windings), sensing the currents from the low voltage windings. The equivalent circuit is determined from relaxation currents with 20'000 s charging duration. In table 10, the parameters of curve fitting are grouped together with the values of the elements of the equivalent circuit determined. Investigations, results of which have already been presented in [Der Houhanessian, Zaengl, 1996a], have shown that the equivalent circuit can also be determined quite well from relaxation currents obtained with shorter charging duration. From C-tanδ measurements at 50 Hz, the values of C_{50 Hz} and tanδ were found to be 687 pF and 1.81%, respectively. The DC resistance R_0 was approximated according to equation (26) as 1.57 TΩ.

Figure 50 compares also the measured depolarization currents with those calculated by means of the equivalent circuit (full lines) and from the polarization current with 20'000 s charging duration (dashed lines), according to equations (21) and (52).
The coincidence of the polarization currents measured $i_{pol}$, measured $i_{depol}$, calculated $i_{depol}$, and calculated $i_{depol}$ from $i_{pol}(t)-i_{pol}(t+T_c)$ are shown in Figure 50. The relaxation currents as a function of charging duration of a single-phase 50/0.5 kV 500 kVA testing transformer. Comparison between the measured and the calculated depolarization currents obtained from the equivalent circuit (full lines) and from the polarization current (dashed lines).

Table 10: Parameters of curve fitting and values of elements of equivalent circuit of the transformer presented in figure 50.

<table>
<thead>
<tr>
<th>i</th>
<th>$A_i$ [A]</th>
<th>$\tau_i$ [s]</th>
<th>$R_i$ [GΩ]</th>
<th>$C_i$ [nF]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$3.59\times10^{-7}$</td>
<td>17.78</td>
<td>5.6</td>
<td>3.19</td>
</tr>
<tr>
<td>2</td>
<td>$1.31\times10^{-7}$</td>
<td>31.62</td>
<td>15.3</td>
<td>2.07</td>
</tr>
<tr>
<td>3</td>
<td>$2.35\times10^{-8}$</td>
<td>100</td>
<td>85.1</td>
<td>1.17</td>
</tr>
<tr>
<td>4</td>
<td>$5.24\times10^{-9}$</td>
<td>316.2</td>
<td>382.0</td>
<td>0.83</td>
</tr>
<tr>
<td>5</td>
<td>$2.29\times10^{-9}$</td>
<td>1'000</td>
<td>873.8</td>
<td>1.14</td>
</tr>
<tr>
<td>6</td>
<td>$9.89\times10^{-10}$</td>
<td>3'162</td>
<td>2'017.8</td>
<td>1.57</td>
</tr>
<tr>
<td>7</td>
<td>$1.88\times10^{-10}$</td>
<td>10'000</td>
<td>9'219.9</td>
<td>1.08</td>
</tr>
<tr>
<td>8</td>
<td>$2.50\times10^{-10}$</td>
<td>31'620</td>
<td>3'747.8</td>
<td>8.44</td>
</tr>
</tbody>
</table>
Figure 51 displays the values of capacitance (real part) and \( \tan \delta \) of this transformer as measured with the dielectric spectrometer and provides a comparison with the values as calculated from the equivalent circuit determined. A good agreement of measured and calculated values for frequencies up to 100 Hz can be noticed. Other examples of calculated capacitance and \( \tan \delta \) of power transformers are presented in [Der Houhanessian, Zaengl, 1996b; Aschwanden et al., 1998].

Figure 52 compares the measured "polarization spectrum" with the calculated one for a charging voltage of 2,000 V. The measurement of the "polarization spectrum" was performed with the Tettex RV-meter. The excitation voltage was applied to the low voltage windings, the outer high voltage windings were grounded. To eliminate the dielectric response contribution of the insulation between the low voltage windings and the limbs of the core, the tank and consequently the core of the transformer have been connected to the potential-controlling connection of the instrument, which is normally used to eliminate the influence of the measuring cable insulation. In this way, it was possible to investigate the same main insulation between low and high voltage windings by the measurements of relaxation currents and the "polarization spectrum". Another example of a comparison of a measured and a calculated "polarization spectrum" of an aged transformer is presented in [Der Houhanessian, Zaengl, 1996b].

Figure 51: Measured and calculated values of the real part of the complex capacitance and \( \tan \delta \) of a single-phase 50/0.5 kV 500 kVA testing transformer.
Figure 52: Measured and calculated "polarization spectra" of a single-phase 50/0.5 kV 500 kVA testing transformer.
7.4.3 Quantitative assessment of the moisture content and ageing state of pressboard within transformers

For any quantitative analysis of the moisture content and ageing state of pressboard used in a power transformer, it is necessary to know the composition of the main insulation for distinguishing the dielectric response of pressboard from the total response of the insulation system. From the simplified model of the main insulation of a transformer or the equivalent equations introduced in section 3.11, it is in fact possible to simulate the relaxation currents of a power transformer in dependence on dielectric properties of oil and pressboard. The required dielectric properties of the oil can be obtained from a sample taken from the transformer measured; those of pressboard, which are not accessible from outside, can be substituted by dielectric properties as measured on laboratory samples with different moisture contents and ageing states. In this way, it is possible to calculate a set of relaxation currents which can then be compared them with the measured ones to find the best fit [Der Houhanessian, Zaengl, 1996b].

Figure 53 shows such a comparison between the measured relaxation currents of transformer "a" as already presented in figure 48 and calculated ones. For all currents calculated, the conductivity of oil was taken as 0.9 pS/m and the relative permittivity as 2.2. The pressboard properties, dielectric response function $f(t)$, DC conductivity $\sigma_0$ and relative permittivity $\varepsilon_r$ have been varied by using those of an unaged "dry" pressboard sample with a moisture content of 0.2%, and aged pressboard samples with final moisture contents of 0.5% and 2.0% (see figure 13 and table 3). The simulations presented show clearly that the change of dielectric properties of pressboard influence mainly the shape of relaxation currents at long times. The quasi identical initial shapes of simulated curves are due to the unchanged value of oil conductivity in these simulations. This predominant influence of oil conductivity on the initial behaviour of relaxation currents can also be used to estimate the oil conductivity of a transformer to be investigated, comparing the measured relaxation currents with calculated ones. The comparison in figure 53 shows that the simulated currents with the dielectric properties of an aged pressboard with the final moisture content of 0.5% agree best with the measured currents.

Figure 54 shows the same procedure of comparison between measured and calculated curves, this time for the investigated transformer "b" (see figure 48). The simulations of currents of transformer "b" have been performed for an oil conductivity of 4.2 pS/m. Once more, an aged pressboard moisture content of 0.5% produces a fair agreement between calculated and measured currents. From the results as presented in figures 53 and 54, it can be concluded that the pressboard materials as used in transformers "a" and "b" are more or less in the same ageing condition and still have a relatively low moisture content [Der Houhanessian, Zaengl, 1997].
Figure 53: Measured and calculated relaxation currents of transformer "a", (see figure 48).

Figure 54: Measured and calculated relaxation currents of transformer "b", (see figure 48).
Figure 55 displays the "polarization spectra" of the transformers "a" and "b" as measured with the RV-meter applying a charging voltage of 2'000 V. The results on multi-layer samples, which have been presented in figures 38 and 45, had already disclosed that the main maximum in the "polarization spectrum" is due to the interfacial polarization, generated from the series arrangement of the pressboard layers and oil ducts, and that the position in time of the maximum corresponds to the time constant of interfacial polarization. In the same manner, the position in time of the main maximum of a "polarization spectrum" measured on a power transformer is equal to the time constant of interfacial polarization between pressboard barriers and oil ducts (see figures 50 and 52). As already shown in figure 45 (curves "a" and "b"), the position in time of the main maximum of the "polarization spectrum" is very sensitive to any change of oil conductivity. This is also confirmed by the results presented in figure 55. It is quite evident that the Tettex "Software for analysis", which is supposed to give moisture content as derived from the position in time of the principal maximum of the "polarization spectrum", will deliver two different values of moisture contents for transformers "a" and "b". In fact, this software quantifies the pressboard moisture content of transformer "a" as 1.7% and that of transformer "b" as 2.6%. However, according to the investigation presented above, it is evident that the values for the moisture content as delivered from the Tettex "Software for analysis" are incorrect.

**Figure 55**: Measured "polarization spectra" of transformers "a" and "b", (see figure 48).
The single-phase transformers "a" and "b" presented in figure 48 belong to a group of 12 transformers, which have been in continuous operation since 1962 within a Swiss hydroelectric power station (Kraftwerke Hinterrhein AG (KHR), Bärenburg). Due to the long period of operation, a general overhaul of these units was scheduled. The transformer "b" from figure 48 was the first one, which was subjected to this overhaul. According to careful inspections, performed on the active part during the overhaul, no replacement of the pressboard material was found to be necessary. Maintenance of the insulation system involved only the usual separate drying and degassing processes of the active part and the original oil. The oil treatment reduced its moisture content from an initial value of about 12 ppm to 6 ppm.

Figure 56 presents the relaxation currents of this transformer, measured before and after this overhaul. The measurement before overhaul (see also figure 48) was performed on-site at 24 °C oil temperature with a charging voltage of 2'000 V. The measurement after overhaul was made at the manufacturer's premises, applying a voltage of 1'000 V. This time, the oil temperature was 20 °C. In the same figure, simulated relaxation currents are also presented, using the dielectric properties of an aged pressboard sample with the final moisture content of 0.5% (see the simulations in figure 54). This simulation has been made by taking the differences of the applied voltage levels and of the oil temperatures into account.

![Figure 56: Measured and calculated relaxation currents of transformer "b" before and after overhaul, (see figure 48).](image-url)
The comparison between the measured and calculated currents before and after overhaul shows only a slight decrease of the relaxation currents after overhaul at long times. By taking the influence of temperature into account, the comparison of initial current shapes indicates a slight increase of the oil conductivity after overhaul. It should be remembered that the active part was re-impregnated after its drying with the original used oil, which had just been dried and degassed. It is evident that drying and degassing of an used oil will decrease its moisture content. However, its conductivity, which is mainly generated by the motion of ionic impurities, will remain more or less the same.

In figure 57, the measured and calculated relaxation currents of a new transformer are compared. The transformer investigated is the same as that presented in section 7.4.1. The currents have been measured in the testing laboratory of the manufacturer applying a charging voltage of 500 V for a duration of 5'000 s. The dielectric properties of pressboard, necessary for the simulation, are taken from new samples with moisture contents of 0.2%, 1.0% and 2.5% (see figure 15 and table 3). The samples with 1.0% and 2.5% moisture content were prepared in the ETHZ laboratory (ETHZ samples). For all simulated currents the oil conductivity was taken as 0.38 pS/m. From comparison between the measured and calculated curves it can be deduced that the moisture content of the pressboard as used within this transformer is a little higher than 1.0%.

![Figure 57: Measured and calculated relaxation currents of a new three-phase 132±11×1.6/12.2 kV 31.5 MVA power transformer, (see figure 49).](image-url)
Figures 58 and 59 show the relaxation currents, measured on-site, of a group of new 3-phase 400/247±17×3.6/30 kV 600 MVA regulating transformers, consisting of 3 single-phase main autotransformers and 3 single-phase regulating units. The measurements were performed between the 30 kV and the 247 kV windings, applying a charging voltage of 1'000 V for a duration of 5'000 s. The average values of the oil temperature during the measurement as read from oil thermometers installed on the transformers are indicated in figures 58 and 59. As already explained in section 6.2, these registered values can be somewhat different from the real temperature within the insulations investigated. Remarkable in this investigation is the quasi-identical shape of currents of the regulating units as shows in figure 59. The differences of the current amplitudes of the main transformers (figure 58) are mainly due to small differences of the oil conductivity.

Figure 60 shows the comparison between measured and calculated relaxation currents for phase S of the main transformers (see figure 58). Analogous to the simulation presented in figure 57, the currents have been calculated in dependence on new pressboard moisture contents of 0.2%, 1.0% and 2.5%. For all simulations, an oil conductivity of 0.56 pS/m was used. The comparison for 26 °C shows that calculated currents for a moisture content of 1.0% in pressboard provide the best match with the measured ones. Figure 61 compares measured and calculated relaxation currents for phase S of the regulating transformers at 22 °C (see figure 59). The oil conductivity as used for this simulation was 0.88 pS/m. Again, the calculated currents for 1.0% moisture content of pressboard give the best match to the measured ones [Der Houhanessian, Zaengl, 1998].
Figure 58: Measured relaxation currents on three single-phase main transformers, belonging to a group of new 3-phase 400/247±17×3.6/30 kV 600 MVA regulating transformers.

Figure 59: Measured relaxation currents on three single-phase regulating transformers, belonging to a group of new 3-phase 400/247±17×3.6/30 kV 600 MVA regulating transformers.
Figure 60: Measured and calculated relaxation currents on phase S of the main transformers (see figure 58).

Figure 61: Measured and calculated relaxation currents on phase S of the regulating transformers (see figure 59).
As already confirmed by the previous results, the initial amplitudes of the relaxation currents are very sensitive to any changes of oil conductivity. Figure 62 presents the relaxation currents of a new 3-phase 241±11×3.5/120/16.5 kV 160 MVA transformer which has been investigated on two occasions: Firstly, the measurements were carried out in the laboratory of the manufacturer before delivery and, secondly, four months later, after installation in the field. The oil temperature of the transformer during the first measurement was 25 °C and during the second one 22 °C. For both measurements, a charging voltage of 200 V was used for a duration of 1'500 s. The initial amplitudes of currents measured on-site are higher than those measured in the laboratory. As already known, this amplification of initial values of currents is due the increase of oil conductivity. This change of oil conductivity is caused by the fact that the oil of such a large transformer is transported in separate tanks to the installation site and it is usually treated a second time before being filled into the transformer. The low conductivity of new oil is very sensitive to such successive handling, therefore a certain increase of its value is quasi inevitable.

Figure 62: Relaxation currents of a new 3-phase 241±11×3.5/120/16.5 kV 160 MVA power transformer, measured a first time in the test laboratory of manufacturer and a second time after its installation in field.

Quite obviously, the calculations presented in this section permit quantifying the moisture content of pressboard in new power transformers. The accuracy of this quantification is directly related to the quality of dielectric response investigations on new pressboard samples in the laboratory. For an application of
this method to aged transformers, it is important to take ageing products into account, whose specific influence on the dielectric properties are not yet known in detail and must be the subject of further investigations [Saha et al., 1997a; Saha et al., 1997b; Saha et al., 1998].
7.5 Additional notes on the procedures used for the evaluation of experimental results and modelling

7.5.1 Determination of DC conductivity and dielectric response function of pressboard samples

To obtain the quantities necessary for modelling, the DC conductivity and the dielectric response function \( f(t) \) of the pressboard samples investigated are determined from the measured relaxation currents. It is quite evident that the values of these quantities obtained are dependent on the determination procedures applied. As already described in section 3.7, the DC conductivity of the pressboard samples (see table 3) was approximated by evaluating equation (27) for a time equal to 200'000 s. The dielectric response function \( f(t) \) of these samples, used mainly in section 7.4.3, was simply approximated from the depolarization currents as measured for a charging duration of 200'000 s, by dividing the initial values of currents up to 10'000 s (less than 1/10 of charging duration) by the applied voltage and geometrical capacitance values (see equation (21)).

In this section, an alternative procedure to determine the dielectric response function \( f(t) \) from polarization currents will be presented and discussed, comparing thus the new quantities derived to those already presented in sections 7.1.7 and 7.4.3. This comparison is done for unaged samples of 0.2% and 1.0% moisture content.

Figure 63 shows the polarization and depolarization currents (curves "1" and "2") of the pressboard sample with 0.2% moisture content as already presented in figure 12. Also plotted are the depolarization current calculated for an infinite charging duration (curve "4"), see section 3.7, and the DC current (curve "3"), which was obtained, according to equation (27), by subtraction of curve "4" from the measured polarization current (curve "1"). It can be clearly observed that the calculated DC current is not at all constant and that the initial values become very small and occasionally negative. This effect is due to the "non-linear" behaviour of "dry" samples (see section 7.1.3), for which the initial difference between the polarization and depolarization currents can be very small or negative (see figure 13). Measuring uncertainties may also contribute to this effect, as the differences are small in comparison to the absolute values.

From this DC current curve two DC component values can be determined. One of \( 1.4 \times 10^{-13} \) A, which is equal to the value at 200'000 s, and another of \( 1.0 \times 10^{-13} \) A, which is determined from the extrapolated DC current curve for times higher than 200'000 s. These values correspond to the DC conductivity values of \( 1.4 \times 10^{-16} \) S/m and \( 1.0 \times 10^{-16} \) S/m (extrapolated value). Now, it is possible to calculate new depolarization currents for an infinite charging duration, by subtracting the above approximated values of the DC component from the
polarization current. These curves are also shown in figure 63 (curves "5" and "6"). Depending on the chosen determination procedure, two different dielectric response functions can be evaluated from curves "5" or "6", which have values which are proportional to the values of these curves (see equation (20)). It is obvious that for this "dry" sample the amplitudes of the dielectric response functions as determined from the currents "5" or "6" at short times (less than 5'000 s) are somewhat lower than those of the dielectric response function determined from the depolarization current.

Figure 63: Relaxation currents of a pressboard sample of 0.2% moisture content. Calculated curves of DC component and depolarization currents for an infinite charging duration. For explanation of calculation procedures see text.

Figure 64 presents the same results as discussed in figure 63, but now for a sample of 1.0% moisture content (see figure 15). It can be seen that for this sample a more stable DC current is obtained (curve "3"). Similar to the previous sample, from this DC current two values for DC components of \(1.1 \times 10^{-12}\) A and \(0.9 \times 10^{-12}\) A (extrapolated value) can be determined. These values correspond to the DC conductivity values of \(1.1 \times 10^{-15}\) S/m and \(0.9 \times 10^{-15}\) S/m (extrapolated value). Also in this case, two different dielectric response functions can be determined from curves "5" or "6", depending on the chosen value of the DC component.
Figure 64: Relaxation currents of a pressboard sample of 1.0% moisture content. Calculated curves of DC component and depolarization currents for an infinite charging duration. For explanation of calculation procedures see text.

It should be mentioned that the determination of a dielectric response function from the polarization current for samples with high moisture content becomes inaccurate and uncertain, due to the appearance of non-linear effects as persistent currents at long times (see figure 15) and due to the big differences in the amplitudes (over two decades) of the polarization and depolarization currents (see again figure 15), which are measured at different measurement ranges of the electrometer with different sensing accuracies.

To show the influence of the change of the dielectric response functions and the DC conductivity values of pressboard, as evaluated from different determination procedures, on simulated relaxation current curves of transformers (see section 7.4.3), the measured and calculated relaxation currents (curves "a") of the 3-phase 132±11×1.6/12.2 kV 31.5 MVA transformer, as already shown in figure 57, are compared with new simulated currents for 0.2% and 1.0% pressboard moisture content (curves "b") in figure 65. It has to be noted that the curves "a" are calculated from the dielectric response functions determined from the depolarization currents and the DC conductivity values of 1.4×10^{-16} S/m and 1.1×10^{-15} S/m of pressboard samples with 0.2% and 1.0% moisture content, respectively (see table 3). The new curves "b" are calculated from the dielectric response functions determined from curves "6" in figures 63 and 64 and the extrapolated DC conductivity values of 1.0×10^{-16} S/m and 0.9×10^{-15} S/m of samples with 0.2% and 1.0% moisture content, respectively.
The amplitude differences between the curves "a" and "b" are mainly due to the change of the dielectric response functions.

All of these attempts to improve the accuracy of the dielectric response function are suffering from the fact that the success of such methods cannot be proven by other independent measurements in the time domain. As, however, the complex capacitance of the samples has been measured by means of the dielectric spectrometer, such results can be compared with those as calculated from the models (see section 7.1.7). Therefore, figures 66 to 68 compare the measured complex capacitance and tanδ values of the pressboard samples with the calculated ones, obtained from the equivalent circuits based on the different determination procedures. The full line curves are calculated from the equivalent circuits, which have been determined from the fitting procedure of depolarization currents, this means with the standard procedure presented in section 3.9 (see also figures 27 to 29). The DC resistances for these equivalent circuits have been obtained from the DC component values of $1.4 \times 10^{-13}$ A and $1.1 \times 10^{-12}$ A of samples with 0.2% and 1.0% moisture content, respectively. The dashed line curves are calculated from the equivalent circuits, this time determined from the fitting of curve "6" of each sample as presented in figures 63 and 64. In this case, the charging duration is considered as infinite in equation (32) and the DC resistances are calculated from the extrapolated DC component values of $1.0 \times 10^{-13}$ A and $0.9 \times 10^{-12}$ A of samples with 0.2% and 1.0% moisture content, respectively. The crossing over of curves for the calculated quantities of the "dry"
sample at low frequencies is due to the lower amplitude of curves "6" with respect to curve "4" for times less than 5'000 s (see figure 63). Figures 65 to 68 disclosed the fact that the different methods of the determination of the dielectric response function and DC conductivity do not have a significant effect on the results of the simulations.

![Graph showing measured and calculated values of the real part of the complex capacitance of pressboard samples with 0.2% and 1.0% moisture content.](image)

**Figure 66:** Measured and calculated values of the real part of the complex capacitance of pressboard samples with 0.2% and 1.0% moisture content. Calculated curves have been obtained from the equivalent circuits determined from the polarization or depolarization currents.
Figure 67: Measured and calculated values of the imaginary part of the complex capacitance of pressboard samples with 0.2% and 1.0% moisture content. Calculated curves have been obtained from the equivalent circuits determined from the polarization or depolarization currents.

Figure 68: Measured and calculated values of $\tan\delta$ of the pressboard samples with 0.2% and 1.0% moisture content. Calculated curves have been obtained from the equivalent circuits determined from the polarization or depolarization currents.
7.5.2 Modelling of dielectric response by means of an equivalent circuit

As already seen in chapter 7, the simple equivalent circuit of section 3.9 determined from measured relaxation currents and power frequency capacitances of the test objects investigated allows one to calculate other forms of the dielectric responses in the time or frequency domain.

The main advantage of the fitting of depolarization currents with a sum of exponential functions (see equation (31)) instead of other fitting models, as power-law [Curie, 1889; von Schweidler, 1907] or a "general response" expression [Jonscher, 1983], is the possibility of the determination of an equivalent circuit, taking the charging duration leading to the depolarization current subjected to the fitting procedure into account (see equation (32)). From this equivalent circuit the relaxation currents resulting from shorter charging duration can be calculated readily as already seen in figures 22, 41 and 50. As seen in the previous section, it is also possible to calculate depolarization currents which would result from an infinite charging duration. It is evident that the amplitude of these currents at long times will be lower than the "true" currents corresponding to an infinite charging duration. This is due to the fact that equivalent circuits determined from the depolarization currents belonging to a limited charging duration contain only a limited share of the information about the relaxation processes. In the same manner, the deviation between the measured and calculated values of complex capacitance and consequently of tanδ at high frequencies can be explained. The present equivalent circuits are determined from the relaxation currents, which are recorded after 1 s application of voltage or of a short-circuit. This means also a limitation of information content of the equivalent circuit for the short time or for the high frequency range.

Equation (31) is particularly suitable for fitting the relaxation currents of multi-layer samples and power transformers due to their shapes which are initially predominantly exponential. The equivalent circuits determined from such currents are also valid for a certain time range below 1 s. This can be checked quite well by comparing the values of complex capacitance or tanδ determined from these equivalent circuits with values measured by means of the dielectric spectrometer.

Figure 69 compares the values of capacitance (real part) and tanδ of the transformer presented in section 7.4.2 determined from the equivalent circuit (see table 10) with those determined from the "Fast Fourier Transform" (FFT) of the depolarization current belonging to a 20'000 s charging duration (figure 50). The values of these quantities measured by means of the dielectric spectrometer are also presented in the same figure.

The relaxation currents of this transformer (see figure 50) have a shape initially markedly exponential with a relatively short time constant, due to its relatively high oil conductivity. Therefore, the equivalent circuit reproduces also quite well the dielectric response for short times or for high frequencies, as it is proven in
The relatively fast deviation of quantities calculated by means of FFT from the measured ones with increase of frequencies shows clearly the advantage of the equivalent circuit to model the dielectric response.

The amplitudes of capacitance and tanδ curves calculated by means of FFT at low frequencies are lower than those belonging to curves determined from equivalent circuits. This is due to the fact that using the equivalent circuit, the quantities in the frequency domain are obtained from the Fourier transform of a depolarization current calculated for an infinite charging duration. The values of this current are obviously higher for long times than those of measured depolarization current with only 20'000 s charging duration, consequently the calculated quantities in the frequency domain have also higher values in the low frequency range compared to those obtained with direct FFT.

It is obvious that the application of the equivalent circuits to reproduce the dielectric responses at high frequencies of the test objects would be less efficient when the relaxation currents initially have a power low time dependence. This can be seen quite well in the case of the simple pressboard samples (see figures 27 to 29), where the deviation between measured and calculated values of complex capacitance and tanδ begins at lower frequencies than with the data of the transformer presented in figure 69. A simple method to reduce this deviation...
is the extrapolation of measured currents to short times. It is evident that the agreement between measured and calculated values at high frequencies would directly depend on how the extrapolated curves match with "real" ones for times less than 1 s. From the results presented in figures 27 to 29 the inefficiency of the extrapolation used in the case of a pressboard sample with 2.5% moisture content can be seen. This behaviour can be well understood studying the curves of extrapolated currents of these samples presented in figure 70. It should be remembered that a simple linear extrapolation in a double logarithmic plot was used to obtain the current values for times less than 1 s. The "master curve" of the pressboard with 2.5% moisture content determined from the depolarization currents measured at temperatures of 5 °C, 20 °C, 35 °C and 50 °C is also presented in the same figure. From the current shapes of the "master curve" and depolarization currents of the samples with 0.2% and 1.0% moisture content a transition region for each curve can be recognised, where a significant increase of the slope occurred. The transition region of the sample with 2.5% moisture is situated at about 1 s and it is not recognizable from the measured depolarization current due to limited amplitude accuracy in the initial phase of recording. As can be seen for this sample, the shape of the extrapolated depolarization current diverges totally from the correct shape as given by the "master curve" and consequently with this extrapolation no significant reduction of the deviation between measured and calculated quantities at high frequencies can be expected.

Figure 70: Measured and extrapolated depolarization currents of unaged pressboard samples with 0.2%, 1.0% and 2.5% moisture content (see figures 15 and 21). "Master curve" of sample with 2.5% moisture content, determined from the temperature dependent depolarization current measurements.
8 Summary and conclusions

In recent years, the measurement and the evaluation of dielectric responses as e.g. recovery voltage, relaxation currents or complex capacitance has become increasingly popular for assessing the state of electrical insulation materials or insulation systems. Without doubt, the application of such measurements to power transformers has been triggered by the proposal of Hungarian scientists to monitor recovery voltages using a special procedure, from which a so-called "polarization spectrum" can be derived and may be used to quantify the moisture content or other effects of ageing of pressboard as used within transformers [Bognár et al., 1990].

The verification of this assertion was one of the motivations to start this project with the aim to study the dielectric behaviour of oil-paper insulation systems, to measure different dielectric responses in function of parameters such as moisture content, ageing products, geometrical configuration and temperature, and to determine the validity limits of linear dielectric response theory. The final goal of this project was to propose a reliable diagnostic method, based on measurements of relaxation currents, for quality assessment of oil-paper insulation in power transformers.

The quantification of dielectric properties of the investigated test objects in the time domain was performed by means of measurement of the relaxation currents, the recovery voltage and the derived "polarization spectrum". In the frequency domain, this quantification was carried out by means of determination of the complex capacitance and the derived values of $\tan$ over a wide frequency range. According to the linear dielectric response theory, all these quantities are related to the basic function describing the properties of dielectric materials in the time domain, i.e. the dielectric response function $f(t)$, or to its Fourier transform, the dielectric susceptibility $\chi(\omega)$.

The relaxation currents and the complex capacitance are in a clear relationship to the DC conductivity, the dielectric response function and the dielectric susceptibility (see chapter 3). This clear relationship to these basic quantities permits a more "simpler" and more fundamental interpretation of the relaxation currents and the complex capacitance in comparison to the recovery voltage or to its derived quantity, the "polarization spectrum".

Due to the fundamental character of relaxation currents, in the time domain, the conversion of relaxation currents to recovery voltages or "polarization spectra" is easier than the reverse procedure. An efficient method to perform this conversion consists of the determination of equivalent circuits, based on relaxation currents and capacitance values measured on the test objects investigated, from which other dielectric responses in the time or frequency domain can easily be calculated. The procedure for determination of such equivalent circuits is
described in section 3.9. It is evident that this kind of simple equivalent circuits can just model the integral dielectric response of the test objects. In case of multi-layer arrangements or power transformers, however, they do not permit one to distinguish between the individual dielectric responses of constituent materials or the contribution of interfacial polarization. Such distinctions can only be achieved with so-called "extended" equivalent circuits (see figures 5 and 7). These circuits are based on equation systems, which describe the dielectric response of multi-layer samples or power transformers in function of the geometrical capacitance and the dielectric properties of the constituent components oil and pressboard (see sections 3.10 and 3.11).

For a correct evaluation of the dielectric response of the main insulation of a power transformer, it was first necessary to investigate the dielectric behaviour of its individual components, i.e. impregnated pressboard and mineral oil, and to study the effect of the combination of these components in multi-layer arrangements of pressboard layers in series with oil ducts.

The main parameters for the investigation of pressboard materials were: moisture content, ageing products and temperature. The measurements were done on new and artificially aged pressboard samples with different moisture contents, prepared in the central laboratory of the Weidmann company and later in the ETHEZ laboratory with procedures as described in section 4.1.1.

The results of dielectric response measurements on pressboard samples, as presented in section 7.1, have demonstrated that moisture has a noticeable influence on the magnitude of dielectric response in the low frequency / long time range, and particularly on DC conductivity, see for example the relaxation currents presented in figures 12 and 15. These results have also shown that ageing products also increase the amplitude of dielectric response, but have less influence on DC conductivity (see figure 13).

The pressboard samples investigated showed in general a linear behaviour. But some non-linear effects, as e.g. space charge injection in samples with low moisture content (see section 7.1.3) or generation of persistent currents in samples with relative high moisture content (see section 7.1), were also observed. Furthermore, for "dry" samples with low moisture content, the calculated values of complex capacitance at low frequencies obtained from relaxation currents were always lower than the measured ones (see section 7.1.7).

The comparison of measured values of complex capacitance and tanδ to calculated ones, obtained from equivalent circuit properties over a wide frequency range (see section 7.1.7), has demonstrated that the dielectric response of impregnated pressboard at low frequency / long time can be modelled well by means of the simple equivalent circuit introduced in section 3.9.

Concerning the temperature behaviour of impregnated pressboard samples, the temperature dependence of loss was deduced by means of a "master curve" technique and characterized by activation energies. The exponential temperature
dependence of the DC conductivity of these samples was also characterized by additional activation energies (see section 7.1.9).

Investigations performed on several new and service-aged mineral oil samples have demonstrated that the dielectric dispersion in the low frequency range is negligible. Therefore, for modelling proposes, the mineral oil can just be represented by its power frequency relative permittivity and its conductivity. The conductivities of oil samples were measured with the "triangular wave method" (see sections 3.7 and 7.2). These measurements have confirmed that low amounts of moisture in oil (< 20 ppm) have no influence on conductivity. Furthermore, it has been shown that the temperature dependence of the oil conductivity obeys an exponential law and can consequently also be characterized by an activation energy (see section 7.2).

After systematic investigations on impregnated pressboard and mineral oil samples, the combination of these two components in multi-layer arrangements has been taken into consideration. These investigations, as presented in section 7.3, have disclosed that the dielectric responses in the time or frequency domains are not only dependent on the dielectric properties of each component, but also on their volume ratios. The measured relaxation currents and complex capacitances (see figures 38, 42 and 43) have clearly shown that the interfacial polarization makes an essential contribution to the total dielectric responses. Parameters such as oil conductivity or volume ratio of oil to pressboard, which are related to the time constant of interfacial polarization, have considerable influence on the shape of these responses. In such arrangements, the dielectric response of pressboard becomes more apparent after completion of interfacial polarization at long times / low frequencies.

The comparison between measured values of complex capacitance and calculated ones obtained from equivalent circuits based on measured relaxation currents (see figures 42, 43 and 44) confirms also the validity of the simple equivalent circuit, introduced in section 3.9, for multi-layer samples. Of course, for an optimal application of this model, it is important to avoid non-linear effects. Measurements in dependence on the voltage level have demonstrated that multi-layer arrangements are more sensitive to non-linear effects than the simple pressboard samples on their own (see section 7.3.2).

For multi-layer samples, the calculated "polarization spectra" based on relaxation currents (see section 7.3.7) have clearly demonstrated that the main maxima in these spectra are due to the interfacial polarization and that their positions in time, which correspond to the time constants of interfacial polarization, depend among other parameters on oil conductivity and volume ratio of oil to pressboard. Therefore, these positions in time must not be considered as a unique criterion for the evaluation of moisture content and ageing of pressboard in multi-layer test objects.
The application of "extended" equivalent circuits or the corresponding system of equations, as introduced in section 3.10, permits one to calculate the total dielectric response of multi-layer samples from geometrical capacitance and dielectric response of single constituent components. Furthermore, it permits one to separate the contribution of interfacial polarization. An example of application of this model is presented in section 7.3.8.

An investigation on new and service-aged power transformers has demonstrated that the dielectric response of the main insulation can quite well be described by means of the basic relations of linear dielectric response theory. The main insulation of a power transformer can be simplified and considered as a composition of three elements, a pressboard barrier in series with an oil duct and a pressboard spacer parallel to these. This composition can be modelled quite well with the "extended" equivalent circuit or a corresponding system of equations as introduced in section 3.11.

The measured relaxation currents on power transformers presented in section 7.4 have again shown the typical predominant exponential time dependence during the initial phase due to the interfacial polarization between pressboard barriers and oil ducts. In these measurements, the dielectric responses of pressboard barriers and spacers became more apparent at long times, after saturation of interfacial polarization.

Analogous to pressboard and multi-layer samples the relaxation currents of power transformers can also be used to determine simple equivalent circuits, from which other dielectric responses can easily be calculated. An example of modelling of a transformer by means of an equivalent circuit is presented in section 7.4.2, where the measured capacitance, $\tan\delta$ and "polarization spectrum" are compared to calculated ones.

The comparison between measured relaxation currents and calculated ones from the "extended" model (see section 3.11) in dependence on dielectric properties of pressboard permits one to make quantitative statements about moisture content and ageing condition of pressboard used within transformers. Several examples of such comparisons for new and service-aged power transformers are presented in section 7.4.3. It is quite evident that the accuracy of such assessments is directly related on the quality of determination of the dielectric properties of pressboard in dependence on moisture content and ageing in the laboratory investigation. To make such comparisons on service-aged transformers, it is important to take ageing products into account, whose specific influence on the dielectric responses (properties) are not yet know in detail and must be the subject of further investigations.

Measured and calculated "polarization spectra" of power transformers and their comparison with other quantities such as relaxation currents (see sections 7.4.2 and 7.4.3) have also confirmed that the main maxima in these spectra are due to interfacial polarization between oil ducts and pressboard barriers; therefore, their
positions in time cannot be considered as an unambiguous criterion for the moisture and ageing assessment of pressboard material used within power transformers.

The investigations in this work showed that the measurement of relaxation currents is an easy-to-apply method for detecting the change of dielectric properties in oil-paper insulation systems. The procedure is applicable as well to laboratory set-ups as to power transformers, even under on-site conditions. Furthermore, taking the facility of interpretation of these currents and their conversion to other quantities into account, it can be concluded that the measurement of relaxation currents and their modelling is an appropriate tool for quality assessment of oil-paper insulation of power transformers.
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