

Oil Conductivity – An Important Quantity for the Design and the Condition Assessment of HVDC Insulation Systems

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HVDC (high voltage direct current) transmission is a very effective way of power transmission and it is necessary to supply the worlds growing amount of energy. In HVDC equipment the major insulating materials are oil and pressboard. Oil conductivity is an important quantity for the design, the diagnosis and the condition assessment of HVDC insulation systems. Unfortunately, insulating oil has a strongly nonlinear conductivity which depends on various parameters (field strength, temperature, water content and ageing) and is time-dependent because of charge carrier drift processes. Measuring methods are required to provide the information necessary for the condition assessment of HVDC systems. Therefore, measurements of new and aged oils are compared and taken into account for a diagnosis of oil-filled HVDC insulation systems. Furthermore, today's standards are analyzed and compared to the so called PDC method. Relations between initial and steady-state conductivities at different temperatures, field strengths and for various oil types are presented and consequences for the condition assessment of insulation systems are discussed.

Categories and Subject Descriptors: Electromobility and Energy Engineering

Additional Key Words and Phrases: HVDC transmission, converter transformer, insulation, liquid, oil, conductivity, dielectric response, time of energization, condition assessment

1 INTRODUCTION

Supplying the worlds growing amount of energy is one of the global challenges. Both rising energy demand and global effort to reduce greenhouse gases are strong stimuli for developing and improving renewable energy sources such as hydro power in remote areas far away from consumption centers. Transportation of bulk power over long distances has to be efficient and therefore HVDC (high voltage direct current) transmission is a good choice. Moreover, offshore wind farms require cables to transfer the power. Unfortunately, the cable capacitances make it inefficient to use AC (alternating current). Therefore, HVDC transmission is a suitable technology for these applications as well. One key component of the HVDC transmission is the converter transformer. Insulating materials are used to insulate conductive parts of the apparatus from grounded parts. Furthermore, energized parts have to be insulated from other energized parts of different voltage potential. Typically, transformer insulation systems consist of a combination of

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mineral oil and solid cellulosic insulation (pressboard and presspaper) and in the case of HVDC converter transformers they need to withstand not only AC and impulse, but in addition DC stresses.

Theoretically, electric fields do not differ for AC and DC as long as the dielectric is homogeneous and has a linear behavior. In practice, these conditions are fulfilled for vacuum and gases if discharges do not occur. For multi-dielectric insulation systems, the type of voltage stress significantly influences the electric field distribution [Hinrichsen and Küchler 2011; Küchler and Bärsch 2010; Küchler 2012; Takahashi et al. 2010]. On the one hand the AC field distribution is determined by the displacement currents and therefore by the permittivities of the insulation materials. On the other hand steady-state DC fields are dictated by the conduction currents and therefore by the conductivities of the insulation materials. Using traditional equivalent circuit elements and assuming a field strength E , the displacement current densities $\partial D/\partial t$ and the conduction current densities J are represented by the currents through a capacitance C (that is determined by the permittivity ϵ) and through a conductance G (that is determined by the conductivity σ) respectively, fig. 1 (left and right).

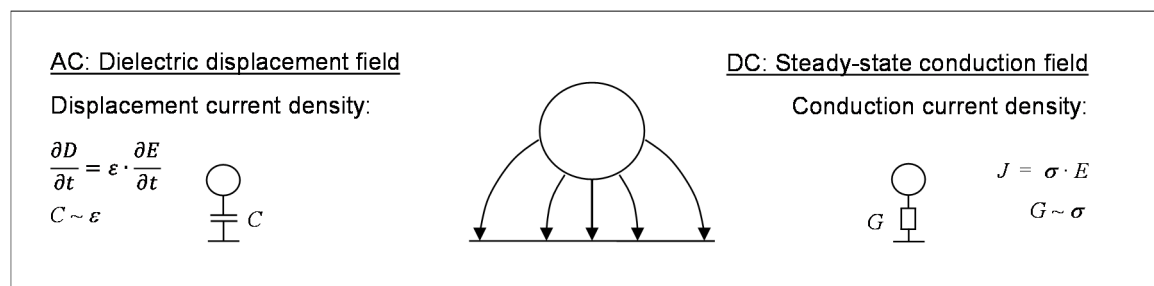


Fig. 1. Basic analogy between quasi-stationary dielectric displacement field (left) and steady-state conduction field (right)

Comparing the equations for the displacement field on the left-hand side with the equations for the conduction field on the right-hand side, there is an analogy between the equations of the time-varying displacement field and the steady-state conduction field in fig. 1.

Nevertheless, in multi-dielectric systems e.g. consisting of two materials ϵ_1, σ_1 and ϵ_2, σ_2 , the permittivity ratio ϵ_1/ϵ_2 and the conductivity ratio σ_1/σ_2 which determine the field distributions will normally be very different. Consequently, displacement fields and conduction fields will also be very different. Permittivities are comparatively well known material properties, but conductivities of insulation materials are inaccurately known, depend on many parameters and are difficult to control [Alj et al. 1985; Hessen and Lampe 1971; Küchler et al. 2003; Lindroth et al. 1994; Novotny and Hopper 1979; Yang et al. 2012]. In HVDC insulation systems both displacement and conduction currents have to be regarded. Additionally, complex polarization and depolarization processes in solids (pressboard) as well as different ion drift processes in liquids (oil) play an important role [Liebschner 2009; Liebschner et al. 2009]. For a reliable transformer design a high safety margin is required. Moreover, there is a remarkable uncertainty with respect to long-term operating reliability of converter transformers in service [Bennett et al. 2010; Lindroth et al. 1994; Saravolac et al. 2010]. That's why there are still many engineering challenges in terms of specific characteristics of HVDC insulation.

An example for the insulation design of an oil-pressboard barrier system at the upper end of a converter transformer winding is shown in fig. 2. The equipotential lines and the field strength

distribution both for the quasi-stationary displacement field (left) and for the steady-state conduction field (right) are calculated.

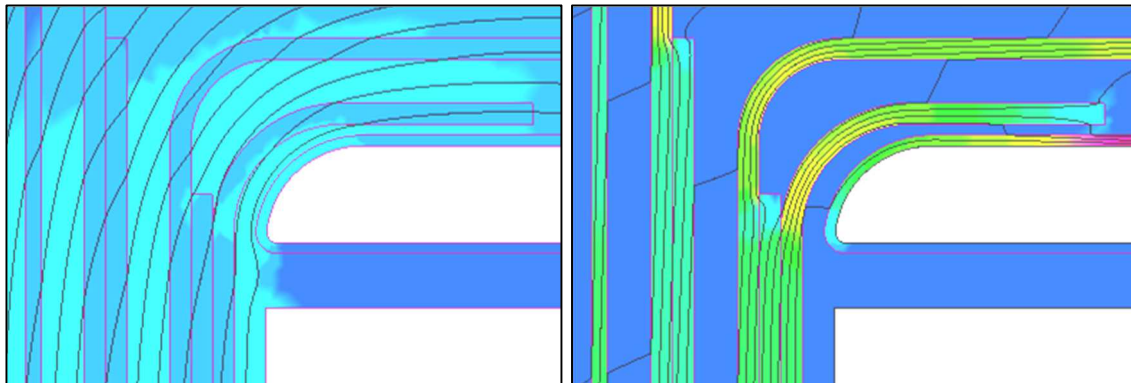


Fig. 2. DC design of an oil-pressboard barrier system at the upper end of a converter transformer winding with equipotential lines both for the quasi-stationary displacement field (left) and for the steady-state conduction field (right)

In case of AC field the function of solid insulation is to achieve the electric strength by subdividing long oil gaps [Dahinden et al. 1998; Moser 1979]. The electric field distribution is determined by material permittivities as mentioned above. The permittivity of transformer oil is approximately half of the permittivity of pressboard. Therefore, the majority of the electric field is applied to oil ducts (fig. 2, left). In case of DC field the function of the solid insulation is totally different, because the DC field distribution is determined by the conductivities of the insulating materials. At 20 °C conductivity of transformer oil is about 10 to 100 times higher than conductivity of pressboard [Hessen and Lampe 1971]. In consequence, the electric field is concentrated in the solid insulation under steady-state DC conditions and oil gaps are barely stressed (fig. 2 right). The function of solid insulation at DC is to insulate almost the whole voltage and hence sufficient thickness is crucial [Moser and Dahinden 1999]. In summary, the material with the lower permittivity or lower conductivity is electrically more stressed than the material with the higher permittivity or higher conductivity respectively. Moreover, transients have to be considered as well, e.g. at a polarity reversal [K uchler et al. 2010].

On the one hand DC insulation designs are often derived from AC designs with some modifications. On the other hand DC field distributions are complexly calculated and simulated. Design of HVDC insulation systems can still be further improved if material behavior is better known than today. But in real insulation systems conductivities change in a large range and so parameters which have been base of the insulation system design are not valid anymore.

Moreover, the design of a HVDC insulation system has to fulfill both AC and DC insulation requirements. Layers with a comparatively low permittivity (oil) have to be thick enough to withstand a significant amount of the total voltage in case of displacement field (AC voltage). Layers with a comparatively low conductivity (pressboard) must be thick enough to withstand nearly all the voltage that is applied to the insulation system in case of steady-state conduction field (steady-state DC voltage). These facts require an engineering compromise in most cases.

Therefore, the understanding of the complex behavior of the HVDC insulation system with changing conductivity values of the involved materials is necessary for an effective design of such insulation systems, e.g. for converter transformers. However, only an appropriate design of the converter transformers guarantees a save electrical energy supply.

In order to get to know the conductivity of the liquid (oil) in HVDC apparatus more detailed measurements of the oil conductivity are necessary. Unfortunately, conductivity of insulating oil is a strongly nonlinear quantity and depends on various parameters. That's why it is difficult to control, to measure and to express mathematically. Detection of an oil conductivity change can be a good indicator for condition assessment of HVDC insulation systems and therefore for HVDC apparatus in service. But first of all, the question concerning the physical background of oil conductivity arises.

2 THEORY OF THE CONDUCTION PROCESSES IN OIL

For the understanding of the parameter dependences of oil conductivity a physical background of the conduction processes is necessary.

Insulating materials consist of nearly non-conductive or weakly conductive materials to avoid or minimize electric currents. Hence, insulating materials are characterized by a high resistance and a weak conductivity respectively. The conductivity is the reciprocal of the specific resistance.

Generally, mineral oils are used as insulating liquids in HVDC transmission systems. Ion conduction and electron conduction can be distinguished in these oils and the conductivity is associated with the motion of numerous charge carriers, e.g. electrons, negative and positive ions or charged particles [Liebschner et al. 2009; Whitehead 1931]. However, at low field strengths electron conduction does not contribute to electrical conduction in mineral oil. At high field strengths electron injection occurs and the conductivity increases [Alj et al. 1985; Bartnikas 1994].

At technical field strengths conductivity of liquids is linked to quantities such as ion mobility and activation energy, and processes such as diffusion, dissociation and recombination in the bulk of the liquid or at an electrode. It is not possible to present a comprehensive theory governing all aspects of conductivity in this article. However, the dominating behavior of conductivity in liquids can be described by ion drift processes [Bartnikas 1994; G afvert et al. 1992].

When a direct voltage (DC) is applied on a dielectric liquid, the current density J in this liquid is defined as the derivate of the transported charge Q with respect to time t per unit area A :

$$J = \frac{1}{A} \cdot \frac{dQ}{dt} \quad (1)$$

If this fraction is extended by dx , the dependence on charge density q and drift velocity v_D can be derived for a single type of ion:

$$J = \frac{1}{A} \cdot \frac{dQ}{dt} \cdot \frac{dx}{dx} = \frac{dQ}{dV} \cdot \frac{dx}{dt} = \frac{dQ}{dV} \cdot v_D = q \cdot v_D \quad (2)$$

Yet, the drift velocity can also be expressed as the product of ion mobility μ and field strength E :

$$v_D = \mu \cdot E \quad (3)$$

If eq. (3) is inserted into eq. (2), the current density is given as a function both of ion mobility and field strength:

$$J = q \cdot \mu \cdot E \quad (4)$$

Moreover, the current density is related to the conductivity σ and to the field strength in dielectric liquids:

$$J = \sigma \cdot E \tag{5}$$

By combining eq. (4) and eq. (5), an equation for the conductivity with electrical and chemical parameters is derived:

$$\sigma = \frac{J}{E} = \frac{q \cdot \mu \cdot E}{E} = q \cdot \mu \tag{6}$$

Thus, in thermodynamic equilibrium the ionic conductivity is given by the sum of the mobility of every type of ions μ_i times the charge carrier density of this ion (charge density) q_i :

$$\sigma = \sum_i (\mu_i \cdot q_i) \tag{7}$$

Due to transient ion drift processes, both oil conductivity and current density can be strongly time-dependent. Immediately after application of a DC voltage to an oil gap polarization processes occur, e.g. by orientation of dipoles, which is not yet a conduction process. Within seconds, conduction currents become dominant, and a so-called “initial conductivity” can be measured, fig. 3. It is determined by positive and negative charge carriers according to equilibrium state between generation and recombination of these charge carriers. The charge carriers are depleted from the bulk oil by DC field within a transit time and charge carrier density and accordingly conductivity decreases to a lower value in equilibrium state at given field strength [Novotny and Hopper 1979]. It is called “steady-state conductivity”. During migration of ions and charged particles, most of the charge carriers are accumulated in proximity of electrodes. In summary, a conductivity value which is derived from a current measurement at an early instant of energization time is normally completely different from a steady-state conductivity.

Conductivity σ is not only time-dependent, but varies for example with temperature, electrical field strength, water content, impurities and aging conditions, too.

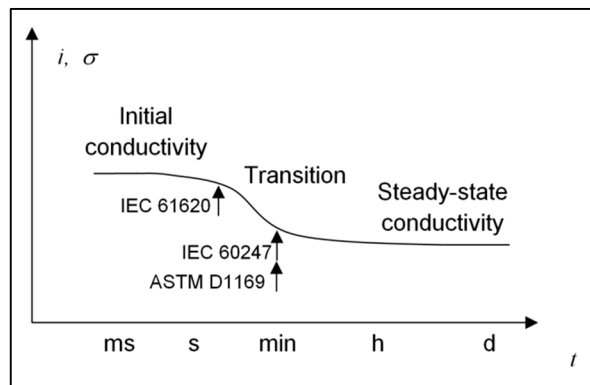


Fig. 3. Current i and conductivity σ vs. stress duration in insulating liquids (schematically), adapted from [Küchler 2009; Whitehead 1931] and relationship with today’s standard measuring methods for conductivity determination

Note: Therefore, measurements of oil conductivity in a HVDC apparatus can yield interesting information about the condition of the insulating system, which can be used for condition assessment. On the one hand, changing conductivity within various parameters may lead to a properly improper design of the insulation system under particular conditions. On the other hand, analyzing oil conductivity in service is a good way of diagnosing HVDC insulation systems.

3 OIL CONDUCTIVITY MEASUREMENTS

For condition assessment purposes as well as for HVDC insulation design purposes parameter dependences of the quantity “oil conductivity” have to be measured. First of all, international standards are discussed. Standards which specify measuring methods and configurations for conductivity determination of liquid materials do exist, but they were not developed especially for HVDC insulation applications [Schober et al. 2012 CIGRÉ]. IEC and IEEE standards, guides and recommendation are taken into account. Secondly a non-standard measuring method is proposed which simulates conditions closer to service conditions in HVDC insulations, e.g. in transformers.

3.1 Standards

Table 1: Standards with references to measurement of conductivity or resistivity of insulating liquids

Standard		IEC 61620, 1998-11 [IEC 61620 1998]	IEC 60247, 2004-02 [IEC 60247 2004]	ASTM D1169-11 [ASTM D1169 2011]
Title		Insulating liquids – Determination of the dielectric dissipation factor by measurement of the conductance and capacitance – Test method	Insulating liquids – Measurement of relative permittivity, dielectric dissipation factor ($\tan \delta$) and d.c. resistivity	Standard Test Method for Specific Resistance (Resistivity) of Electrical Insulating Liquids
Scope	Quantities	<u>Dielectric dissipation factor</u> (Conductivity measurements are a means of dissipation factor determination only)	<u>Relative permittivity, dielectric dissipation factor ($\tan \delta$), d.c. resistivity</u>	<u>Specific resistance (resistivity)</u>
		Authors' remark: By definition, conductivity is related to an initial current density during a very short period of time.	Authors' remark: By definition, d.c. resistivity is related to “steady-state current density”.	Authors' remark: By definition, d.c. resistivity is related to a current density “at a given instant of time”.
	Method ^{*)}	Current measurement, trapezoidal voltage	Current measurement, dc voltage	Current measurement, dc voltage
Field Strength ^{*)}		≤ 0.1 kV/mm	≤ 0.25 kV/mm	0.2 to 1.2 kV/mm (upper limit in order to avoid ionization)
Time of energization ^{*)}		0.4 - 5 s (trapezoidal square wave, $f = 0.1$ to 1 Hz, rise time 1 to 100 ms)	1 min	1 min direct polarity / 5 min short circuit / 1 min reversed polarity
Temperature		Ambient or elevated temperature	Ambient or elevated temperature	According to mutual agreement
^{*)} In the case of resistivity / conductivity measurements only				

The intention of the standard IEC 61620, 1998-11, [IEC 61620 1998] is the determination of the dielectric dissipation factor $\tan \delta$ by means of an auxiliary conductivity measurement. Nevertheless, it is not intended to standardize conductivity measurements. By definition in this standard, the quantity conductivity is related to an initial current density during a very short time of energization.

The standard proposes to measure dielectric properties by means of a trapezoidal test voltage (trapezoidal square wave, $f = 0.1$ Hz to 1 Hz, rise time 1 ms to 100 ms) at very low field strengths (≤ 0.1 kV/mm). Measurements should be done at ambient temperature or at elevated temperature. (Note that the conductivity changes a lot with temperature.) This standard defines to calculate permittivities from the displacement current I_C (capacitive current) during the rise time and the conductivities are calculated from the conduction current I_R during the time with constant voltage (0.4 s to 5 s). Thereby, only the initial oil conductivity value at very low field strength is determined.

IEC 61620 specifies a procedure that gives reproducible results because of a fast changing trapezoidal voltage with a half-cycle duration that is significantly lower than the transit time of ions in the oil gap. Thus, the ions are not swept out by the field and an initial low-field conductivity value is determined which can be a reproducible fingerprint for comparisons between different oils. Nevertheless, the initial conductivity is different from the steady-state and transient conductivities in insulation systems and it is impossible to establish a relationship between the initial and the steady-state conductivity, see section 5. Steady-state conductivities have to be measured additionally.

The standard IEC 60247, 2004-02, [IEC 60247 2004] is primarily for reference tests on unused liquids, but also applicable to liquids in service. A voltage is applied and the current through the insulating liquid is measured (step response measurement). With configuration geometry the resistivity (and the conductivity) is calculated. Measurements should be done at ambient temperature or at elevated temperature. The standard specifies a maximum field strength of only 0.25 kV/mm to the liquid in a special test cell and to measure the conductivity at $t = 60$ s. The approach with the constant DC voltage coincides with steady-state field stress in HVDC insulation systems. By definition, DC resistivity is related to a steady-state current density. Unfortunately, no steady-state conditions are reached after 60 s and conductivity is still changing at that time. In comparison with HVDC transformer test and service conditions today's standard measuring procedure for oil conductivities is performed both with very short times of energization and at very low field strengths. Therefore, measurements of dielectric properties according to this standard do not provide all information necessary for characterization of HVDC insulation behavior.

Moreover, conductivity values are dependent on stress history of the oil sample because of ion drift processes. Reproducible measurements would either require a determination of an electrical pre-conditioning prior to the measurement [Hjortstam et al. 2012; Liebschner 2009] or sufficient relaxation time without any stress prior to the measurement in order to reach a thermodynamic equilibrium of the ions.

In 2011, a new release of the American standard ASTM D1169-11 [ASTM D1169 2011] has been published. This standard specifies a current measurement with a DC voltage applied at a field strength between 0.2 and 1.2 kV/mm. Tests can be performed on unused liquids and liquids in service. Measurements are proposed to be done at ambient and at higher temperatures according to mutual agreement. For routine testing, temperatures are usually set to room temperature, 85 °C or 100 °C. For acceptance tests, measurements are generally made at a temperature of 100 °C. The time of energization can be based on a mutual agreement as well, but in general the time of energization according to this standard is $t = 60$ s. This standard specifies to average two measurements with both polarities in order to compensate for polarity-related effects. But unfortunately this is not enough. It has been shown that a conditioning needs a number of

subsequent polarity reversals [Liebschner 2009]. Moreover, time of energization proposed in this standard is short compared to transformer test and service conditions.

In the mentioned standards, initial values (valid in a time range up to a few seconds) and one-minute values (neither representative for initial nor for steady-state conductivities) are determined. This is not sufficient, because conductivities may significantly change with time. A conductivity value which is derived from a measurement at an early and predefined instant of time can be very different, i.e. more than one order of magnitude, from its steady-state value. The relation between the time dependence of oil conductivity and the times of energization according to today's standards are schematically visualized in fig. 3.

Furthermore, applying today's standards with low field strengths in comparison with transformer test and service conditions does not yield a realistic situation for highly stressed nonlinear insulation materials as the field dependences of the conductivity in dielectric liquids are neglected. Therefore, standard measurements of dielectric properties do not provide all information necessary for characterization of HVDC insulation materials. Consequently, it is necessary to develop additional methods for the determination of oil conductivity.

At the moment, these questions are discussed in the CIGRÉ Joint Working Group A2/D1.41 (HVDC transformer insulation – Oil conductivity) [JWG A2/D1.41 2013] in order to develop recommendations for measurements of oil conductivity throughout the lifecycle of HVDC transformers.

The authors of this paper think that a new procedure should cover all results obtainable by standard measurements after a few seconds (IEC 61620), after 60 s (IEC 60247 / ASTM D1169) and the steady-state conditions. Furthermore, electric field strengths should be high enough to simulate real HVDC transformers.

3.2 PDC Method

Based on the measuring method in IEC 60247 a step response measurement in time domain is suggested by the authors. The dielectric system response of the insulating material contains all necessary information about the oil for design, diagnosis and condition assessment. The here proposed method is based on PDC measurements (polarization and depolarization currents). It consists of three phases:

- (1) A depolarization (relaxation) phase without field in order to discharge any remaining polarization,
- (2) a polarization phase with DC test voltage applied and
- (3) a depolarization phase without voltage (terminals short-circuited), fig. 4.

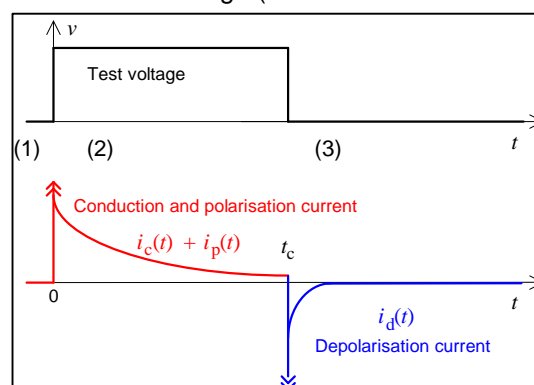


Fig. 4. Voltage step and dielectric system response of mineral oil according to the PDC method

In phase (2) the sum of conduction current $i_c(t)$ and polarization currents $i_p(t)$ and in phase (3) the depolarization current $i_d(t)$ are measured. They can be visualized in a log-log diagram for evaluation purposes. This provides a visualization of short, medium and long term processes in the insulating materials and allows for direct comparison of polarization and depolarization currents [Alff et al. 2000; Der Houhanessian 1998].

Note: Conductivity is calculated from the conduction current component during phase (2). The depolarization currents measured during phase (1) and (3) are auxiliary quantities. They are used for detection of possible offsets during measurement and for detection of possible polarization currents. For oils depolarization currents are negligible in most of the cases.

A high voltage V is applied to a test configuration and the current is measured over a sufficiently long period of time, i.e. several hours. In case of oil, the measured current $i(t)$ is directly proportional to the time-dependent conductivity and polarization currents can be neglected. The conductivity $\sigma(t)$ can be calculated with the electrode area A and the oil gap width d :

$$\sigma(t) = \frac{d}{A} \cdot \frac{i(t)}{V} \quad (8)$$

The test cell consists of a glass vessel. Liquids (about one liter) are measured between plane guard ring electrodes with a high-voltage design (measuring area about 78 cm²). The electrodes are separated by spacers between guard ring and high-voltage electrode, fig. 5 (left). The electrode configuration is immersed in the oil sample in order to prevent partial discharges for measurements up to 10 kV/mm (for liquids).

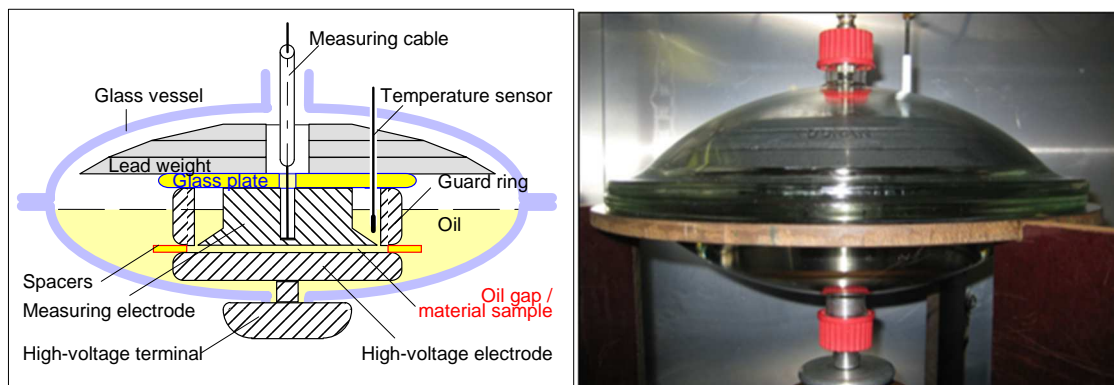


Fig. 5. High-voltage test cell for PDC measurements (schematic and photo)

With this test cell, measurements of insulating liquids are accomplished within a wide range of field strengths (normally 0.1 kV/mm up to 10 kV/mm) and at different temperatures (e.g. 20 °C, 50 °C, 90 °C). These conditions are more relevant both for test and service conditions for HVDC equipment than the conditions defined in today's standards. Moreover, the time of energization is three hours (10 800 s) in order to come close to steady state. Currents are recorded and conductivity values are calculated continuously. Consequently, conductivity values according to the PDC method can be evaluated at different instants of energization time and compared to values derived from standard measurements. The concept is to use the same test cell and the same test procedure for all materials which have to interact in a HVDC insulation system, e.g. solids (pressboard) and liquids (oil).

4 PARAMETER DEPENDENCES OF OIL CONDUCTIVITY

In this paragraph results from measurements according to the PDC method are presented. The measurements were performed at different conditions in order to evaluate the influence of parameters such as time of energization, temperature and field strength both for HVDC design and condition assessment purposes.

4.1 Time of Energization

In fig. 6 the conductivity of a commonly used mineral oil for HVDC applications (oil type 1.3) is calculated from the measured currents according to eq. (8). The dependence on the time of energization is shown in a log-log diagram for three temperatures at a field strength of 1 kV/mm. The time dependence of the oil conductivity can clearly be seen, compare with fig. 3. The initially high conductivity shifts steadily to a significantly lower steady-state conductivity. The depolarization current can be neglected in oil, because oil does not store large amounts of charges, in contrast to solid materials. That is why the depolarization currents are not shown here. This time dependence has been evaluated for various measurements with different new oil types. All of them show a similar time characteristic, which confirms the ion drift model.

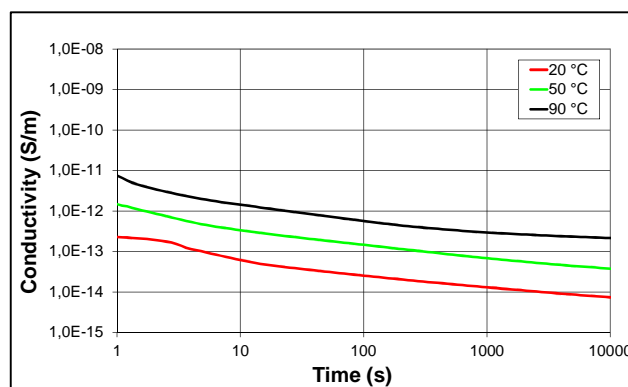


Fig. 6. Conductivity as a function of time and temperature at 1 kV/mm (Oil type 1.3 is a commonly used mineral oil, unaged.)

Furthermore, the transit time of the ions at 20 °C can be identified in this figure at round about $t = 4$ s and about $t = 1.5$ s for 50 °C. The 90 °C transit time is below 1 s and thus cannot be seen in this diagram. The ion drift processes in this particular oil last several hours. Moreover, it should be noted that the steady-state conductivities are about one to two orders of magnitude smaller than the initial conductivity, depending on measurement temperature. This is a typical case for new, unused mineral oils.

4.2 Temperature

Moreover, a temperature dependence of the oil conductivity is obvious in fig. 6 as well. This is predominantly the result of the temperature dependence on the viscosity of the liquid. The viscosity η is inversely proportional to the mobility of molecules in the oil which is linked to a Boltzmann temperature relation with the activation energy E_A and the Boltzmann constant k_B :

$$\frac{1}{\eta} = \frac{1}{\eta_\infty} \cdot e^{-\frac{E_A}{k_B \cdot T}} \quad (9)$$

It means that the liquid viscosity decreases with an increase of temperature. According to Walden's Rule, the product of the liquid viscosity η and the ion mobility μ is constant:

$$\mu \cdot \eta = \text{constant} \quad (10)$$

Therefore, a decrease of the liquid viscosity leads to an increase in the ion mobility:

$$\mu = \mu_\infty \cdot e^{-\frac{E_A}{k_B \cdot T}} \quad (11)$$

Note: Besides the temperature dependence of ion mobility, dissociation rate of dissolved molecules in the liquid is temperature-dependent, too.

According to eq. (7), the oil conductivity σ is proportional to the ion mobility. If the mobility is increased because of a temperature increase according to eq. (11), the conductivity increases as well. This is the physical background of why the various curves in fig. 6 look similar.

4.3 Field Strength

Furthermore, it is interesting to evaluate the effect of different field strengths on the conductivity and on the transit time. Therefore, conductivity measurements have been performed at 20 °C and within a wide range of field strengths between 0.1 kV/mm and 10 kV/mm and an oil gap width of 3 mm. Thereby, the field strengths occurring in a HVDC apparatus are covered. Oil type 1.4 is a mineral oil for HVDC applications. It can be compared to oil type 1.3 in fig. 6 and shows similar conduction behavior. Fig. 7 shows the conductivity of this oil type in dependence of time and applied field strength at 20 °C.

Note: For higher voltages (above 2 kV) the currents during the first few seconds after voltage application are not measured, because the high voltage source needs a few seconds for stabilization and for that reason the conduction currents in the first few seconds are completely covered by much higher displacement currents.

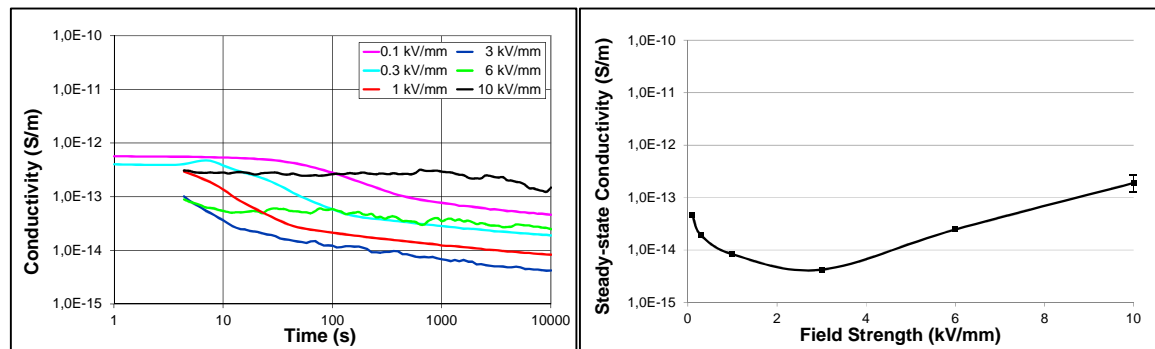


Fig. 7. Conductivity of oil type 1.4 (new, unused mineral oil) measured at 20 °C as a function of time and field strength (left) and dependence of steady-state conductivity on electric field strength (right)

When analyzing curves in fig. 7 (left), different time dependences of the oil conductivity are obvious for different field strengths. Initially, the conductivity is comparatively high and decreases with time of energization. A transit time t_t can be estimated from the curves as well. It is defined as the time which a charge carrier needs to drift from one electrode to the other. Thereby it drifts with the drift velocity v_D and has to tread the path with the length d (oil gap width). The dependences are expressed in eq. (12), e.g. [Gäfvert et al. 1992]:

$$t_t = \frac{d}{v_D} = \frac{d}{\mu \cdot E} \quad (12)$$

The transit time is directly proportional to the oil gap width and inversely proportional to the applied electric field strength. If there is no temperature change, ion mobility does not vary and is regarded to be a constant in the considered field strength range. Table 2 lists transit times estimated from conductivity measurements for different field strengths according to fig. 7 (left).

Field strength E	0.1 kV/mm	0.3 kV/mm	1 kV/mm	3 kV/mm	6 kV/mm	10 kV/mm
Transit time t_t	200 s	60 s	20 s	6 s	3 s	not assessable

Table 2: Transit times as a function of field strength according to fig. 7 (left)

The values of the transit times in Table 2 fit very well to the field strength dependence according to eq. (12), assuming a charge carrier mobility μ of about $10^{-10} \text{ m}^2/\text{Vs}$. The charge carrier mobility varies a lot within different oil types [Yang et al. 2012]. Interpretation of transit times and different measuring methods of these transit times are not further discussed in this publication. For detailed information see literature, e.g. [Denat 2011; Dikarev 2005; Hjortstam et al. 2012].

Furthermore, fig. 7 (right) presents the steady-state conductivity of oil type 1.4 in dependence on the electric field strength at 20 °C. The pronounced dependence indicates that the field strength must be considered for conductivity measurements. The limitation of today's standards becomes obvious, since they define just one field strength of low to minor value to be applied. The field strength dependence of oil conductivity follows a "bath tub curve". This is also considered in ASTM D1169: "The dc volume resistivity of new oil, particularly at room temperature, has been shown to be a function of both electrical stress and electrode spacing. The resistivity has been found to have a maximum value when the applied electrical stress is about 2 kV/mm; electrical stresses either below or above this critical value yield lower values of volume resistivity" [ASTM D1169 2011].

The field strength dependence can be explained considering ion generation and ion drift processes. Ions can be generated in two ways: In the bulk of the liquid or at interfaces (e.g. metal electrode and liquid) [Alj et al. 1985]. At low field strength ions are transported under the force of the electric field to the counter electrode. They are accumulated and are not or only partly neutralized [Liebschner 2009; Liebschner et al. 2009]. The field strength is not high enough to inject a significant number of electrons into the liquid. The higher the field strength, the faster the ion drift process (drift velocity). The viscosity of the liquid has to be considered as well. At higher field strength, more ions are accumulated in front of the counter electrodes and a new layer with the opposite charge in respect to the electrode charge is built up. These accumulated ions are no longer contributing to the conduction current through the liquid. At field strength between 1 – 3 kV/mm, a conductivity minimum is reached. Beyond this conduction minimum generation of new charge carriers leads to an increase in conductivity [Theoleyre and Tobazéon 1985]. For detailed discussions see [Alj et al. 1985; Lewis 1994; Pontiga and Castellanos 1996]. Fig. 7 (right) confirms the conductivity dependence on the electric field strength published in [Wahlström 1976].

4.4 Aging

In fig. 8 (middle) the conductivity of another mineral oil (oil type 3.1) is depicted for the same measurement conditions as in fig. 6. This oil has a higher initial and a higher steady-state conductivity than oil type 1.3, fig. 8 (left). The time dependence and the temperature dependence of both oils are obvious. The transit times of oil type 3.1 are slightly longer than the transit times of oil type 1.3 and for both oils the transit times are temperature-dependent. The shape of the PDC curve correlates to a change in the insulating properties of the oil [Schober et al. 2012 CMD].

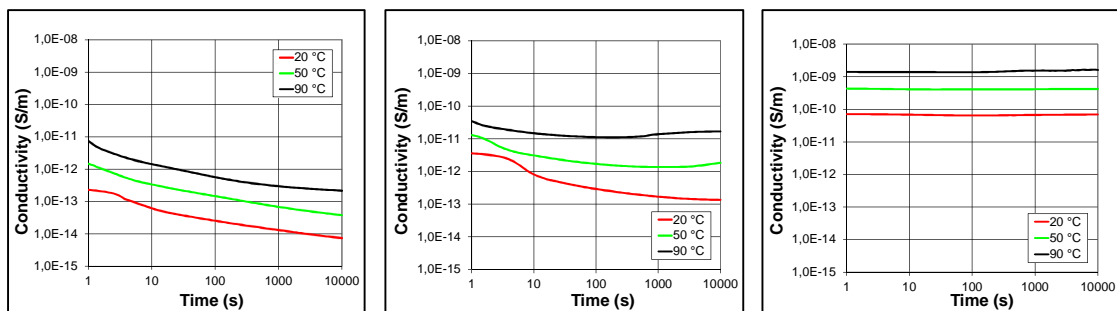


Fig. 8. Conductivity as a function of time and temperature: Oil Type 1.3 (left), oil type 3.1, a more conductive oil than oil type 1.3 (middle) and oil type 5.1, a heavily aged mineral oil (right)

Furthermore, dissipation factor measurements for the different oils were performed with a Schering Bridge at 20 °C and 90 °C, Table 3. The dissipation factor $\tan \delta$ for oil type 3.1 at 20 °C is low, but at 90 °C it is appreciably higher.

Oil Type	Oil Type 1.3	Oil Type 3.1	Oil Type 5.1
Dissipation factor at 20 °C	$0.1 \cdot 10^{-3}$	$0.9 \cdot 10^{-3}$	$14.0 \cdot 10^{-3}$
Dissipation factor at 90 °C	$10.0 \cdot 10^{-3}$	$20.0 \cdot 10^{-3}$	$260.0 \cdot 10^{-3}$

Table 3: Dissipation factors measured with a Schering Bridge for three mineral oils

Furthermore, the DC step response current of a heavily aged oil sample (oil type 5.1) is measured and the conductivity is calculated, see fig. 8 (right). This particular oil sample was taken from a shunt reactor in service for more than 21 years. Initial and steady-state conductivity are extremely high, almost $1 \cdot 10^{-10}$ S/m at 20 °C. The conductivity in this case does not decay with time. Probably conductive ageing by-products, e.g. acids, dominate the conduction behavior of this oil and mask the ion drift processes. The dielectric dissipation factor $\tan \delta$ measured at 20 °C is high and even higher at 90 °C, Table 3.

Thus, a condition assessment of the insulating oil can be based on conductivity measurements according to the PDC method. The shapes of the curves differ very much between new and unused oils, fig. 8. The decomposition products of the oil together with by-products of cellulose degradation result in enhancement of oil conductivity and in dielectric losses [Küchler et al. 2007]. After all, the PDC measuring method seems to be a good way to determine the conductivity of insulating oils as a tool for design engineering, for design review stages and for condition assessment throughout the lifecycle of oil filled HVDC power apparatuses.

5 CONDUCTIVITY RATIOS

On the one hand, the value of the steady-state conductivity of oil is required for assessing the electric DC field. On the other hand, this measurement is time consuming (several hours) and therefore the question arises whether an extrapolation from measurements with short energization times is possible. That would be the case if a firm relationship between short and long duration measurements exists. This relationship will be discussed in this chapter.

The time dependence of oil conductivity has been discussed and explained in terms of physics. The initial conductivity is generally higher than the steady-state conductivity.

In order to look for relationships between these conductivities, three conductivity ratios are calculated, using measurements with short durations ($t = 1$ s, $t = 60$ s) and long durations ($t = 3\,600$ s, $t = 10\,800$ s):

$$V01 = \frac{\sigma(t = 1 \text{ s})}{\sigma(t = 10\,800 \text{ s})}; \quad V60 = \frac{\sigma(t = 60 \text{ s})}{\sigma(t = 10\,800 \text{ s})}; \quad V3600 = \frac{\sigma(t = 3\,600 \text{ s})}{\sigma(t = 10\,800 \text{ s})}; \quad (13), (14), (15)$$

V01 relates the short duration conductivity as defined by IEC 61620 (and measured here by the PDC method) to the approximate steady-state conductivity. V60 links the suggested measurements at 60 s (IEC 60247 and ASTM D1169) to the approximate steady-state values. V3600 is a compromise for determining the steady-state conductivity with a reduced time of energization which is currently discussed in CIGRÉ Joint Working Group A2/D1.41 [JWG A2/D1.41 2013].

Lots of oil types and batches have been investigated at different temperatures and field strengths and the conductivity ratios have been calculated. The conductivity ratios V01, V60 and V3600 are plotted as function of temperature for various mineral oil types and at a field strength of 1 kV/mm. The water content of the measured oils was below 5 ppm if not otherwise specified.

Note: The different curves, e.g. for oil type 1.1 in fig. 9, belong to different samples of the same oil type.

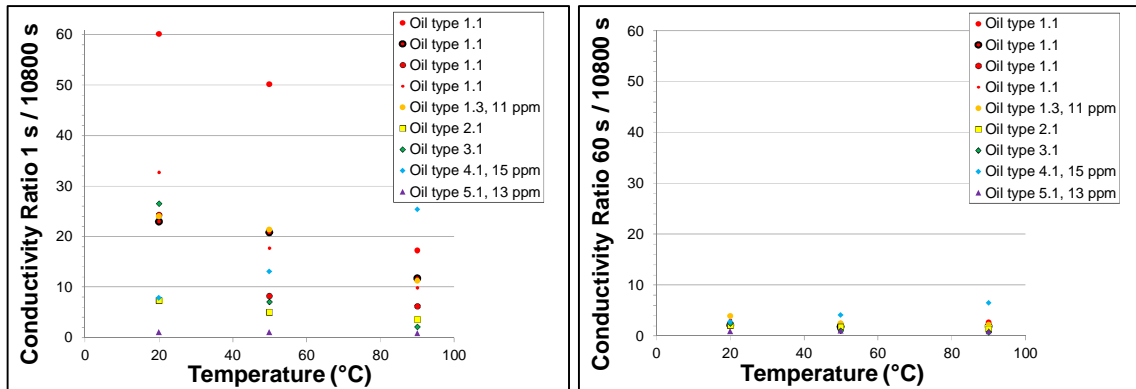


Fig. 9. Conductivity ratios (V01 left, V60 right) as function of temperature at 1 kV/mm.
Water content of the measured oils was below 5 ppm if not otherwise specified

In fig. 9 it can be seen that the short-term conductivities at 1 s are in most cases more than one order of magnitude higher than the steady-state values. Moreover, the conductivity ratios are smaller for increased temperature. In contrast, the 60 s conductivity values are significantly closer to the steady-state values and do not vary that much with temperature. All ratios are between one and seven. A ratio of V3600 would come close to one. That means that a conductivity measurement of one hour energization time yields results that are close to the steady-state condition, e.g. to the conditions in a converter transformer, see fig. 10.

Furthermore, the dependences of the ratios on the electrical field strength and on the steady-state conductivity (low and high conductive oils) have been investigated [Schober et al. 2012 CIGRÉ] and are depicted below. For a more detailed consideration, only V60 and V3600 are plotted here, fig. 10. Note that the scaling of the y-axis has been changed in comparison with fig. 9 in order to differentiate the oil types and parameter dependences more clearly.

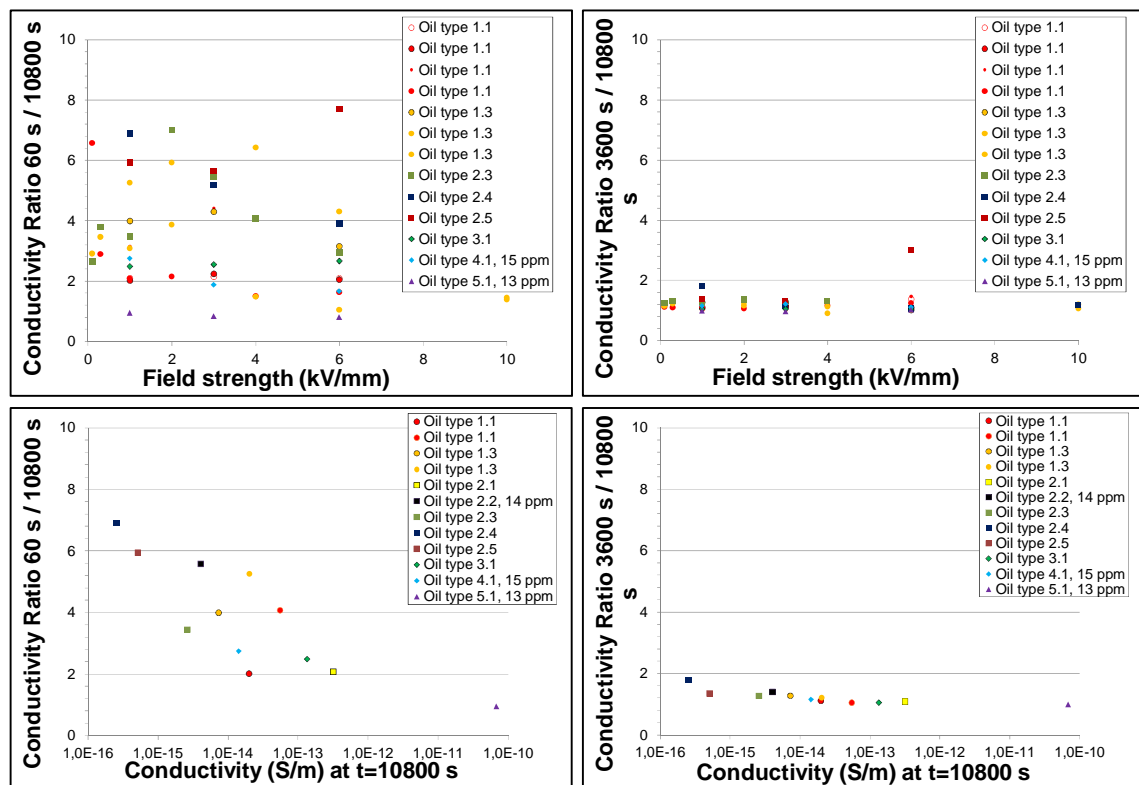


Fig. 10. Conductivity ratios (V60 left and V3600 right) as function of field strength at 20 °C (top) and as function of the steady-state conductivity at 20 °C and 1 kV/mm (bottom). Water content of the measured oils was below 5 ppm if not otherwise specified.

The dependence on field strength resembles the temperature dependence (fig. 9) and the ratios decrease distinctly with increasing oil conductivity (more conductive oil types). The conductivity ratios differ not only with oil type, they vary also within the same oil type from batch to batch, see for instance the different samples of oil type 1.1.

The conductivity of oil type 5.1 exhibits nearly no time dependence, fig. 8 right, and the conductivity ratio does not depend on temperature or field strength. The conductivity of that heavily aged oil is very high due to aging products and the above mentioned parameter dependences are obviously negligible.

Since there are many different and significant individual deviations for different types and batches of oil, it has unfortunately to be concluded that there is no chance to establish a firm relationship between short-term and long-term conductivities.

6 CONCLUSION

For DC applications, conductivities of insulating materials are important quantities for determination of electric field distributions. Yet, conductivity of insulating liquids in HVDC converter transformers, e.g. mineral oils, is not constant but depends on various parameters and parameter combinations. These parameter influences have to be considered.

In order to find procedures for oil conductivity measurements, the time dependence of the conductivity has to be regarded for condition assessment throughout the lifecycle of HVDC components as well as for design and for design review stages. Short-term conductivities can be one to two orders of magnitude above steady-state values that are relevant for test and service operation. Moreover, temperature influences (Arrhenius law) and field strength influences (bath tub curve) have to be kept in mind. The dependences of oil conductivity on the mentioned parameters lead to the necessity of measuring oil conductivity in dependence on these parameters. Therefore, conductivities have to be measured at field strengths above the comparatively low field strengths according to standards.

When calculating conductivity ratios, there are significant differences for different types of oil and even for different batches of the same type of oil. It has to be concluded that there is no chance to establish a relationship between short-term and long-term conductivities. The dependences of oil conductivity ratios on different parameters are not clear enough for any mathematical extrapolation. Measuring methods at short energization times and low field strengths according to standards don't consider the HVDC transformer service and test stresses.

Using PDC measurements the relevant parameter dependences of oil conductivity can be investigated. For that purpose long-lasting measurements under different temperatures and field strengths have to be done. Afterwards all important information is available for the design of insulation systems. Both the shape of the curves and the steady-state conductivity values can serve as aging indicators of insulation system and can therefore support a condition assessment.

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