Stellingen

behorende bij het proefschrift

Charges and Discharges in HVDC Cables
in particular in mass-impregnated HVDC cables

Marc Jeroense
Delft, 24 maart 1997
1. Bij de ontwikkeling van nieuwe generatie HVDC kabels is het nodig diagnostische technieken, zoals partiële ontladingstechnieken, aan testprogramma's toe te voegen.

2. Het $q-n$ diagram is een goede basis om de kwaliteit van HVDC kabels te beoordelen.

3. Het ruimteladingsgedrag in geïmpregneerd papier is in verrassende mate reproduceerbaar.

4. De geldverslindende jacht naar de fundamentele deeltjes is maatschappelijk nog slechts te verantwoorden door haar spin-offs.

5. In de twintigste eeuw heeft de wetenschap niet-deterministische methoden als neurale netwerken, chaostheorie en vage logica als waardevol erkend. Ook de christelijke religie zou er goed aan doen het vraagteken in haar denken bewust toe te laten en opnieuw op waarde te schatten.

6. Het spreekwoord "Tijd is geld" is verouderd en dient vervangen te worden door "Tijd is meer dan geld".

7. In de geschiedenis is de physica een van de toestsstenen van de geloofsvoorstellingen van het Christendom gebleken.

8. In een machtsvacuüm kan de druk hoog oplopen.

9. De discussie tussen de aanhangers van het creationisme en het evolutionisme is een nutteloze en gaat voorbij aan een hogere vraag: "Ligt er een hogere macht ten grondslag aan het heelaal?".

10. De vraag: "kunt U toveren?" dient een vast onderdeel te zijn van een sollicitatieprocedure.
Charges and Discharges in HVDC Cables

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When you are a Bear of Very Little Brain, and you Think of Things, you find sometimes that a Thing which seemed very Thingish inside you is quite different when it gets out into the open and has other people looking at it.

*The House at Pooh Corner*
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Summary:
CHARGES AND DISCHARGES IN HVDC CABLES

Mass-impregnated HVDC cables are just as reliable as high voltage AC cables. However, there is still a lack of knowledge concerning HVDC cables. In addition, the tests for HVDC cables are less well developed than those for high voltage AC cables. The purpose of this study is to gain a better understanding of the HVDC cable and to propose a better-developed set of tests. This is of particular interest in respect to new generations of HVDC cables which have higher operating voltages and higher power transmission capacities.

In Chapter 1, a brief introduction is given on HVDC cables, partial discharges, space charges and test rules.

Chapter 2 describes the electric field and charge distributions in an HVDC cable dielectric at different voltage stages. Electric field calculations at DC voltage are far more complex than those at AC. At DC voltage, the field depends on geometry, voltage, conductivity, temperature, space charge and time. Software has been developed that calculates the field and charge distributions in HVDC cables at every possible stage.

It follows from these field calculations that testing a cable subjected to a low environmental temperature with polarity reversals is a more severe test than that of a cable subjected to a high environmental temperature.

At sufficiently high environmental temperatures, the leakage current of an HVDC cable distorts the field. Eventually, the heating of the cable by the leakage current may lead to a thermal breakdown. This is of importance when testing oil-pressure cables and for the development of new insulation materials at DC voltage.
Chapter 3 concerns the partial discharge behaviour of HVDC mass-impregnated cables. It is possible to relate specific discharge patterns to the underlying physics of the cable. Characteristic discharge patterns after switching off the load are a result of pressure changes in the cable and a growth of the number of voids due to compound contraction. Partial discharges just before breakdown are monitored and evaluated.

In Chapter 4, the space charge behaviour in mass-impregnated paper is investigated. The space charge distributions in paper are surprisingly reproducible. This is in contrast to space charge patterns in plastics, which may differ greatly per type and batch.

If a layer of impregnated paper lies next to an electrode, charges are injected into the paper. The resulting space charge distributions are always of the homocharge type. The growth and decay of the charges follow specific patterns. Both the growth and the decay in time can be described by two time constants. These observations are, to a great extent, independent of electrode type, polarity and voltage.

The effect of the homocharge distribution is a field enhancement in the bulk of the paper. Thin, highly impermeable papers and low resistive insulating oils show the lowest field enhancements.

In the case of stacked paper layers, space charges do not cross the paper border to the next layer. The injected charge is, therefore, limited to the first paper layer adjacent to the electrode. This has an implication in respect to the design of HVDC cables: thin, highly impermeable papers should be used next to the conductor and the lead-sheath.

Chapter 5 presents a physical model that predicts the charge observations as described in Chapter 4. It is likely that the conduction in impregnated paper is of the ionic kind and it is most probable that some kind of Schottky injection occurs at a paper-electrode interface. The total model uses these conduction and injection mechanisms as well as a recombination of charge carriers that depends on the local carrier concentration. The predictions of the model remain valid, regardless of a wide variation of the parameters. The model is a solid confirmation of the soundness of the space charge observations.

Chapter 6 proposes tests on HVDC paper cables. The test proposal uses the existing CIGRE test recommendations as a basis, but the recommendations are extended with the knowledge gained in this work.
The knowledge of the electrical life-line of HVDC cables is incomplete. For this reason, it is necessary to add diagnostic tests for the new generations of HVDC cables. Possible diagnostic tests are: the partial discharge test and the dielectric current test. Regarding partial discharge tests, the $q$-$n$ diagram and the quality number $Q$ are proposed as measures to discriminate between "good" and "bad" cables.

Cables and accessories should be tested at an environmental temperature that reflects the actual service conditions.

Factory joints should be tested in the same way as the cable.

M.J.P. Jeroense
Summary
1.1 General

High voltage AC is used mainly in energy supply, while high voltage DC (HVDC) is used mainly in non-energy applications. There are several everyday applications in which HVDC techniques are used in non-energy applications: think of television sets and computer screens. In medical and military science, HVDC is used in X-ray equipment, electron microscopes, image intensifiers and radar. Even satellites, taking care of our world-wide communications, use HVDC in their broadcasting equipment. The exception is the HVDC cable, which is used for submarine power transmission: the HVDC cable is a typical example of an energy application.

The understanding of the dielectrics, which are stressed under HVDC, is far behind that of the dielectric phenomena at high voltage AC. The main reason for this is the economic impact of the electricity supply that is operated at high voltage AC. A failure in the energy grid may lead to tremendous costs for the users and for the companies that produce and distribute the electric energy. High reliability and long life are therefore a must for AC components. This need for reliability has led to intensive research and development programs through the years. The result is a good knowledge of the dielectric phenomena at AC voltage.

A failure in HVDC non-energy equipment has less negative consequences. Fewer people are affected by such a failure and the faulty component may be exchanged for a new one for relatively little money. The need for a thorough understanding of the dielectric behaviour at DC voltage was therefore not so high as for AC.
An exception is formed by HVDC systems, which form part of the power grid. HVDC systems and cables are starting to play a larger and larger role in the world-wide energy grid. This increases the need for a better understanding of the dielectric phenomena under DC voltage. This works aimes at a better understanding of the HVDC cable.

Additional knowledge is needed in the following fields:

1. **Electric fields.**
   The electric field distribution at DC voltage differs greatly from that at AC voltage. The field distribution at DC is determined by the conductivity $\sigma$ of the insulation material and by the permittivity $\varepsilon$. The conductivity is not constant, but depends strongly on the temperature and the electric field. Surface charges and space charges play an important role too. As a result, the intermediate fields are space, temperature, and time dependent. Altogether, this makes the determination of the electric field at DC voltage a far more complex matter than the equivalent case at AC voltage. The theory of DC fields, in particular in cables, is given in Chapter 2.

2. **Space charges.**
   As space charges play an important role, because they distort the electric field, it is highly desirable to measure them. One of the measurement techniques that is able to measure space charges is called the Pulsed Electro-Acoustic (PEA) measurement [44]. This thesis presents the principle of the method as well as test results on impregnated cable paper (see Chapter 4). To the best knowledge of the author, this work is the first to present results of space charge measurements on impregnated cable paper. Chapter 5 presents a physical model that predicts the observations that were made.

3. **Partial discharges at DC voltage.**
   Much is known about partial discharges at AC voltage. However, discharges at DC voltage behave in a different way. The theory of partial discharges at DC voltages, as well as the results obtained with tests on HVDC submarine cables, are discussed in Chapter 3.

4. **Ageing and breakdown.**
   The ageing and breakdown mechanisms at DC voltage differ from those of the AC case [55]. There are, however, indications that the concept of the life-line, as known from AC technology, is also valid at DC voltage [32, 55]. The knowledge of the life-line of HVDC cables is discussed in §6.1. The partial discharge phenomena, before breakdown, are discussed in §3.4. Two types of thermal breakdown are discussed in §2.3.
1.2 HVDC cables

5. Test rules.
Few test rules exist for HVDC equipment, there are some proposals and recommendations only. Kreuger [55] and Fromm [32] published test proposals, the former regarding energy as well as non-energy equipment, the latter on non-energy equipment only. Electrical test recommendations exist for HVDC cables with paper insulation [22], published by CIGRE. Some other standards (examples: [5]) deal briefly with testing of DC insulating materials.
Chapter 6 presents test rules for HVDC paper cables. They are based on these recommendations [22] and are extended with the knowledge that is gained in this work.

1.2 HVDC cables

HVDC techniques are in use in the power grid in cases where high voltage AC techniques simply cannot be used or have large disadvantages. If long distances have to be bridged, high voltage AC cables can no longer be used due to the high capacitive currents. From a certain length of cable on, the capacitive current is so large compared to the current that has to be transported, that it is no longer feasible to use AC voltage [47]. This break-even point depends on many factors, but at present lies around 30 kilometers for submarine cables and around 500 kilometers, for overhead lines [89].

Other reasons for using HVDC techniques in energy applications are [89]:
- connecting power grids that operate at different frequencies.
- connecting power grids that operate with different control procedures.
- connecting power grids that, in the AC case, would result in one large power grid with a too high short-circuit current.

There is no special need for the use of HVDC cables in these cases. The connection may be made using a back-to-back convertor.

A brief review of the several types of HVDC cables will be given below.
- **Mass-impregnated paper insulated cable**.

  This type of cable is mainly used in long sea crossings. The cable needs no oil feeding and has a proven reliability. Theoretically, there is no physical limitation on cable length. The first HVDC cable in the world

---

1 The mass-impregnated HVDC cable is also referred to as the MIND cable (mass-impregnated non-draining cable).
was a cable of this type and is known as the Gotland cable. It connects the Gotland island with the Swedish mainland. The link (100 kV, 20 MW, 100 km) was constructed in the year 1954 and was upgraded to 150 kV, 30 MW in 1970 [39]. The cable with the highest voltage (450 kV), power (600 MW) and length (250 km) up till 1996 is the Baltic cable, connecting Germany with Sweden [30]. Information about some other projects involving this type of cable may be found in [94, 86, 11, 6, 38, 4].

- **Oil-filled cable.**
  This type of cable is also paper-insulated, but impregnated with thin oil and has a proven reliability as well. It has a higher transport capacity due to its higher continuous electrical design stress and higher operating temperature. The disadvantage of this cable, however, is the need for oil feeding once every 10 to 20 kilometers. This makes it less interesting for long water crossings. Several connections exist; the best known is the St Lawrence rivercrossing in Canada (500 kV, 625 MW, 5 km, 1992) [25]. The Møllerhøj cable, which is a special case of an oil-filled cable, needs no oil feeding due to its special flat design: the expansion of the oil is taken care of by the cable itself. However, it needs special stop-joints if larger depths have to be crossed. The only cable of this type in service so far (400 kV, 600 MW, 175 km, 1995) connects Denmark with Germany [85].

- **Gas-pressure cable.**
  This type of cable is also insulated with paper, but impregnated, as it were, with gas under high pressure. The cable is seldom used as an HVDC cable. In fact, only one link is in service: the Cook Strait cable (250 kV, 300 MW, 39 km, 1965), connecting the Northern and Southern islands of New Zealand [26]. The cable is of the internal gass-pressure type.

- **Extruded cables.**
  At the time of writing, extruded cables are still unreliable at DC voltage. No commercially available cable exists so far. Accumulation of space charge in the insulation is the biggest problem that has to be solved. Therefore, this type of cable is still in the development stage [55, 65]. However, with the introduction of the space charge measurement methods, it may be expected that the development of this type of cable will be accelerated.

The present work aims at the further understanding of the HVDC cable, in particular the mass-impregnated paper HVDC cable.
1.3 Partial discharges

The risk of partial discharges at AC voltage, which substantially reduce the voltage life of equipment, is well known [57, 72, 58]. In general, partial discharges lead to material erosion and treeing, which in turn may result in a total breakdown of the object. In AC cables, harmful discharges may occur at protrusions located at the inner or outer semi-conducting screens or at inclusions and voids located in the insulation.

There is no hard evidence that there is a direct relation between partial discharges at DC voltage and breakdown of the stressed object [55, 32, 91]. However, partial discharges may indicate weak points in the insulation where a breakdown may be initiated by another process. Although the discharges might not be the cause, they often are the predecessor of a breakdown [55]. For this reason, it is useful to measure partial discharges also at DC voltage. The same type of defects as those mentioned in the case of AC cables may be critical in DC cables. In the case of the mass-impregnated paper cable, the voids especially are critical defects which play an important role in the physics of that cable. These voids come into existence during load changes.

Partial discharges may be detected in several electrical and non-electrical ways [57]. Electrical discharge detection makes use of the charge displacement that can be measured as a current in the external circuit. The most common method integrates the displacement current over its time of occurrence and the result is called the discharge magnitude \( q \). This method is used in this work (see Chapter 3).

1.4 Space charges

If a gradient exists in the conductivity \( \sigma \) or the permittivity \( \varepsilon \) of an insulation material, where:

\[
\nabla \frac{\varepsilon}{\sigma} \neq 0, \quad (1.1)
\]
it may be derived [32] that space charge accumulates in the insulation, according to

$$\rho = aE \cdot \sqrt{\varepsilon} \frac{\varepsilon}{\sigma} \quad (\text{for } t \to \infty),$$

(1.2)

in which $E$ stands for the electric field strength.

A gradient in $\varepsilon/\sigma$ may occur for several reasons. The conductivity $\sigma$ of most materials depends on temperature and field. An HVDC cable is a typical example of where this situation occurs. If the cable is loaded, this will result in a temperature gradient across the insulation. This temperature gradient results in the accumulation of space charge, which inverts the field (see Chapter 2).

Another reason for a gradient in $\varepsilon/\sigma$ occurring is that the structure of the insulation material is never perfectly homogeneous. Crystalline and amorphous regions may be found in one piece of insulation material. The crystalline and amorphous regions have different conductivities and permittivities, thus resulting in a gradient in $\varepsilon/\sigma$ and in accumulation of space charge [55].

Space charge will also accumulate at interfaces. This holds both for an insulator-insulator interface and for an insulator-electrode interface.

The layered structure of a paper cable serves as an example for an insulator-insulator interface. Charges will accumulate at successive paper-oil interfaces (see Figure 1.1). This is understandable, as the conductivity of oil is higher than that of impregnated paper, which results in a gradient in $\varepsilon/\sigma$.

Figure 1.1 Charges at the paper-oil interfaces in the insulation of a paper cable.
In the case of insulator-electrode interfaces, one often speaks about homocharge and heterocharge (see Figure 1.2). One speaks about homocharge if the space charge that accumulates near an electrode has the same polarity as the electrode (see Figure 1.2a). This situation occurs if charges are more easily injected by the electrode-insulator interface than that they are transported through the bulk insulator material. Homocharge releases the electric stress of the insulator-electrode interface and increases the stress in the insulator material.

One speaks about heterocharge if the polarity of the space charge that accumulates near an electrode is opposite to that of the electrode (see Figure 1.2b). This situation occurs if the bulk insulator material transports charges more easily than that they are extracted by the insulator-electrode interface. Heterocharge increases the electric stress of the insulator-electrode interface and releases the stress in the insulator material.

In practice, space charge will indeed accumulate in insulation that is stressed under DC [98, 63, 55, 27]. The charge will contribute to the electric field. The field may be enhanced at certain locations in the insulation. In some cases, this contribution may be high enough to initiate a breakdown. For this reason, it is important to have quantitative knowledge of this space charge. There are today various non-destructive methods of measuring space charge (see Chapter 4). In this thesis, the Pulsed Electro-Acoustic (PEA) method is used [46, 44, 47]. The principle of the method is based on an interaction of a pulsed electric field with space charges inside the insulation: as a result, these charges generate acoustic waves that can be detected externally (see Chapter 4) by a piezo-electric device.

### 1.5 Test rules

It has been stated in §1.1 that tests for HVDC equipment are less well developed than those for high voltage AC equipment. Concerning paper insulated HVDC cables, there are semi-official test recommendations. These test
recommendations are generally known as the ELECTRA 72 document [22]. All known HVDC submarine cable links that have been tested according to these recommendations have, up till now, proven to provide a high availability. The requirements of these test recommendations are considered sufficient for the current generation of HVDC cables \((U \leq 450 \text{ kV}, P \leq 600 \text{ MW})\).

The recommendations are based on overvoltage testing and heat cycling. Apart from a loss angle test, no diagnostic tests are mentioned.

One could argue as to whether these test recommendations are sufficient for a new generation of cables with service voltages \(U\) higher than 450 kV and transmission capacities \(P\) higher than 600 MW. For several reasons (see §6.1), it is desirable to add diagnostic tests to the existing recommendations.

On the basis of the knowledge that has been generated and is presented in this thesis, proposals are made for new tests for HVDC cables (Chapter 6).

1.6 Object of present study

HVDC cables have proved to be reliable in service. There is still, however, a lack of knowledge, especially concerning field calculations, partial discharge behaviour and space charge phenomena at DC voltage. The work aims to reduce this lack of knowledge

- by introducing methods to calculate electric fields in an HVDC cable at different voltage stages and different temperatures (Chapter 2).
- by having performed partial discharge measurements at DC voltage at different voltage stages and during a breakdown test (Chapter 3).
- by having performed space charge measurements on mass-impregnated paper insulation material (Chapters 4 and 5).
1.6 Object of present study

Tests for HVDC cables are less well developed than for high voltage AC cables.

- Another aim of this work is, therefore, to propose a better developed set of tests, based on the current test recommendations for HVDC paper cables [22], but extended with the knowledge concerning electric fields, partial discharge measurements and space charge measurements.
Electric Fields

HVDC cables are designed both for electric fields under steady-state conditions as for those that occur under transient conditions. At this moment 30 kV/mm is considered to be a safe steady-state DC field for mass impregnated cables [24]; a value of 85 kV/mm is taken as a safe value under transient conditions [24]. Quantitative knowledge of the electric fields in the dielectrics is therefore important.

Field calculations at DC voltages are far more complex than at AC voltages. This is, to a large extent, due to the strong non-linear behaviour of the insulation. The field will differ per stage, i.e. whether the voltage has just been switched on or has already been present for a long time, whether the polarity has just been reversed or the voltage has been lowered to zero.

In this chapter, it is shown how to calculate these fields in the consecutive stages: section 2.1 presents a definition of the different stages, in §2.2 the fields during the different stages are calculated.

Ohmic insulation losses are normally not taken into account, as their effect on the electric field is quite small. Section 2.3 however, shows in which case it is not permitted to ignore the losses and it shows the effect on the field strength if this effect is taken into account.
In §2.4, the electric field is calculated when an impulse is superimposed on a DC voltage.

2.1 Different stages

DC fields differ per stage. For this reason the calculation and explanation of these fields is performed per stage. The different stages are described using
Figure 2.1, following the proposals of Kreuger [55]. We first focus on the upper part of the figure. In stage I, the external voltage $U$ is raised. At the beginning of this stage, the cable contains no space charge and there is no temperature drop across the insulation. The electric field is determined by the geometry and the permittivity only. We speak of a capacitive field. During stage II, the voltage $U$ has already reached its final value. The electric field, however, is changing from a capacitive field to a resistive field. The field during this stage is an intermediate field. A pure resistive field exists in stage III. In all these three stages a load current $I$ may be present, that heats the conductor of the cable. If a load current is present in stage III, it is switched off in stage III', which is a special case of stage III. The voltage is lowered to zero in stage IV. A field still exists after the voltage has been removed. The lower part of Figure 2.1 shows the stages during (stage V) and after (stage VI) a polarity reversal. During stage VII, the field after a polarity reversal has become stable.

2.2 Fields at different stages

The electric fields that occur during different stages are treated in this section. Before going into detail, some general comments are given.

Electric fields at AC voltage are determined by the permittivity $\varepsilon$, the geometry of the object and the applied voltage $U$. Space charge is usually not generated at AC fields and may therefore be disregarded. These parameters are independent of environmental parameters such as, for instance, temperature.

Electric fields at DC voltage are determined by the conductivity $\sigma$, the permittivity $\varepsilon$, the geometry of the sample, the applied voltage $U$ and space charge density $\rho$. 
2.2 Fields at different stages

The conductivity depends both on the temperature and on the electric field according to the empirical relation

$$\sigma = \sigma_0 \exp(\alpha T) \exp(\gamma E),$$

(2.1)

in which $\sigma$ stands for the conductivity at a certain temperature and field, $\sigma_0$ stands for the conductivity at 0°C and 0 kV/mm, $\alpha$ is the temperature dependency coefficient, $\gamma$ is the field dependency coefficient and $E$ is the electric field strength [17, 77, 52, 75, 21]. A value of $1 \times 10^{-16} \, \Omega^{-1} \, \text{m}^{-1}$ is taken for $\sigma_0$, $0.1 \, ^\circ\text{C}^{-1}$ for $\alpha$ and 0.03 mm/kV for $\gamma$, which are values in use for most impregnated paper types. Equation (2.1) assumes that the insulation is homogeneous, which is a correct assumption for a macroscopic examination of oil paper insulation. Examinations made on a microscopic level require a refinement of the theory. The physical basis behind the non-linear behaviour of $\sigma$ is described in Chapter 5.

The general effect of the temperature and field dependency of the conductivity $\sigma$ is explained with the aid of Figure 2.2. The effect of the temperature dependency of the conductivity is that of a field inversion. In an unloaded cable the highest field strength is found near the conductor. In a loaded cable there is a temperature gradient. Near the conductor, at $R_0$, the temperature is higher than near the lead-sheath, at $R_i$. Due to the temperature dependency, the conductivity near the conductor will be higher than near the lead-sheath. Thus, the highest field strength is pushed towards the lead-sheath. The field distribution is inversed.

The effect of the field dependence is a levelling of the field strength as can be seen in Figure 2.2. The difference between the field strength near the conductor and that near the lead-sheath becomes smaller.

In the following sections, all calculations will be performed on a 1600 mm$^2$ copper, 450 kV paper cable, with an internal radius (up to and including the
carbon paper over the conductor) $R_i = 23.2$ mm and an external insulation radius (which reaches to, but excludes the carbon paper under the lead-sheath) $R_o = 42.4$ mm. The insulation thickness is 19.2 mm. The relative permittivity $\epsilon_r$ is 3.5 and the conductivity $\sigma_o$ was $1 \times 10^{-16}$ $\Omega^{-1}$m$^{-1}$. It will hereafter be referred to as "the standard" cable.

2.2.1 Stage I - Raising the voltage

In stage I, the external voltage $U$ is raised to its desired value. This takes a short time, usually a few seconds. This time is much shorter than the time constant of the insulation, which is determined by the permittivity $\epsilon$ and the conductivity $\sigma$ of the insulation. For this reason the field that is present in stage I is a capacitive field. The field may be calculated using [53]

$$E = U \frac{1}{r \ln \frac{R_o}{R_i}}, \quad (2.2)$$

where it has been supposed that the permittivity $\epsilon_r$ is independent of radius $r$. This is the same formula as used for AC cables.

The field for the standard cable is drawn in Figure 2.3. It can be seen that the highest field strength is found near the conductor, as known from the AC cables.

Equation (2.2) may be used only if the cable contains no space charge.

![Figure 2.3 The capacitive field distribution in stage I with $U=450$ kV.](image-url)
2.2.2 Stage II - After raising the voltage

After having raised the voltage (stage I), the field changes from a purely capacitive stage to a purely resistive stage. This section describes the field between these stages; the field is therefore named an intermediate field.

The field cannot be calculated using an equation in a closed mathematical form. It has to be calculated numerically. The field\(^2\) can be computed using Gauss' law, the continuity equation and Ohms law

\[ \nabla \cdot E = \frac{\rho}{\varepsilon}, \tag{2.3} \]

\[ \nabla \cdot J + \frac{\partial \rho}{\partial t} = 0, \tag{2.4} \]

\[ J = \sigma E, \tag{2.5} \]

in which \(J\) is the current density. Suitable boundary conditions have to be chosen in order to calculate the actual situation:

- the field distribution \(E\) at \(t=0\).
- a function describing the temperature as a function of radius and time, \(T(r, t)\).

A computer program has been written (see Appendix F) that solves the above equations as a function of time \(t\) and radius \(r\). The accuracy of the program for calculating fields has been checked in two ways:

1. The field at \(t=0\), calculated with this software, must be a purely capacitive field. This purely capacitive field can be calculated according to equation (2.2) and be compared to the results of the computer calculations. It was found that the error is always less than 0.5%.

2. The field at \(t \to \infty\), calculated with this software, must be a purely resistive field. However, the purely resistive field cannot be calculated exactly (see §2.2.3). An exact error calculation is therefore not possible. But the purely resistive field may be calculated numerically in a more

\(^2\) It has been assumed that \(\nabla \times E = 0\).
direct way than above (see §2.2.3) as the field is solved in space only and not in time. For this reason it is assumed that the latter method of calculating the resistive field has a smaller error than the method used in this section. Comparison of the two results gives a reasonable error estimation. This estimated error was always less than 0.5%.

With regard to the load of the cable, we may calculate three different situations in stage II (see Figure 2.4).

![Diagram](image)

**Figure 2.4** The different situations in stage II as explained in the text.

1. The intermediate field $E$ while the cable is not loaded, $I=0$.
2. The intermediate field $E$ after the cable has just been loaded.
3. The intermediate field $E$ of a stable loaded cable. The current has been raised long before and the temperature distribution in the cable is stable.

Situation 1 is not very interesting as the field is hardly changing. There is no temperature drop across the insulation, so there will be no field inversion. The field will slightly change due to the field dependency of the conductivity (compare the lines "no load, $\gamma=0.03$ mm/kV" and "no load, $\gamma=0$" in Figure 2.2).
2.2 Fields at different stages

Situations 2 and 3 are more interesting because of the field inversion. The intermediate fields in these two situations are almost the same and change from a purely capacitive field to the inverted resistive field. They differ in the rate of change only.

For further explanation we limit ourselves to situation 3.

Figure 2.5 shows the field distribution in the standard cable at different times. The lead-sheath at $R_e$ has a stable temperature of 35°C and the temperature drop across the insulation is 15°C. At $t=0$ the voltage was switched on and resulted in a capacitive field distribution. The intermediate field is shown for every 10 minutes. The purely resistive field is represented by the line at $t=\infty$.

The intermediate fields show that there is a point in the cable, roughly in the middle, where the field is hardly changing. The field at the conductor is decreasing more quickly than the field at the lead-sheath is increasing. This is explained by the fact that the insulation near the conductor is 15°C warmer than the insulation near the lead-sheath and has therefore a higher conductivity; the time constant near the conductor is then smaller.

*Time constant*

The time constant of a dielectric that consists of two materials with different permittivities $\varepsilon$ or conductivities $\sigma$ is relatively easy to determine [55]. The case of an actual cable is more complex, as the conductivity depends on place and time.

To get an idea of the time constants, the time $t_{63\%}$ at which the field has changed for 63% is considered. This time is calculated for the change in the field at a point in the insulation adjacent to the conductor.
CHAPTER 2 Electric Fields

and for a point adjacent to the lead-sheath. The temperature drop across the insulation was 15°C and the external voltage was 450 kV. The computation was performed using different lead-sheath temperatures $T_s$. The results are represented by the straight line in Figure 2.6.

It is concluded that the time constant is lower for the insulation near the conductor. This is understandable, as the temperature and therefore the conductivity is higher near the conductor. Further, the time constant is exponentially inversely proportional to the temperature of the cable. The higher the temperature, the shorter the time constant.

Observe that the calculations of the time constant have to do with the electric time constant of the cable only, as a stable temperature distribution was taken as a starting-point. If the temperature is changing (for instance during heating or cooling of the cable) the thermal time constant of the cable and its environment takes part in the process as well.

2.2.3 Stage III - Stable field

In stage III, the electric field has become a stable resistive field. Due to the temperature dependency and the field dependency, there is a gradient in the conductivity. If such a gradient in the insulation occurs, a space charge is present as may be derived from the Maxwell equations [55, 49]. The space charge generates a field, commonly named the charge-induced field. This charge-induced field causes the field inversion and the effect of levelling which have been shown in §2.2 and Figure 2.2.

First, we start with the calculation of the field, second, we calculate the total insulation resistance of the cable and, third, we calculate the space charge distribution.

Field
The exact electric field including the effect of temperature and field dependence is given by

$$ E = U \frac{r^{k-1} \exp(-\gamma E)}{R_i} \int_{R_i}^{R_s} r^{k-1} \exp(-\gamma E) dr, $$

(2.6)
in which \( k \) is given by

\[
k = \frac{\alpha \Delta T}{\ln \left( \frac{R_o}{R_i} \right)}.
\] (2.7)

This equation can be calculated in a numerical way only. The equation is derived in Appendix E.

In Figure 2.7, the fields are calculated for different temperature drops \( \Delta T \). With no temperature drop, the highest field strength is found near the conductor and is 29 kV/mm (calculated with the dimensions of the standard cable as described in §2.2). For high temperature drops (>15\(^\circ\)C), the field near the lead-sheath may become higher than the highest possible field strength near the conductor. In the middle of the insulation, a point is found where the field is not influenced by the temperature drop.

From equations (2.6) and (2.7) it is derived that the field distribution does not depend on the absolute temperature but on the temperature drop only. (This holds only if the small influence of ohmic losses due to the leakage current is not taken into account - see §2.3).

One may disregard the field dependency \( \gamma \) of the conductivity, as, in that case, the field may be calculated analytically. Starting from equation (2.6) and setting \( \gamma = 0 \) we find

\[
E = U \frac{r^{k-1}}{R_o},
\] (2.8)
which may be written as

\[ E = \frac{k}{R_0} \left[ \frac{1 - \left( \frac{R}{R_0} \right)^k}{\left( \frac{r}{R_0} \right)^{k-1}} \right]. \tag{2.9} \]

From equation (2.9) it is seen that the stress distribution varies with \( r^{k-1} \). It means that for \( k=0 \) (that is, no temperature drop), the distribution is a hyperbolic function like in the capacitive stage. For \( k=1 \), the stress distribution is linear and does not depend on the radius. For values of \( k \) larger than 1, the stress is inversed.

Equation (2.9) is the approximation used to calculate the DC field taking into account the temperature dependency, but disregarding the field dependency. This approximation is commonly used and is also found in literature [17, 80, 77]. However, care must be taken as the approximation gives large errors for high field strengths and for high temperature drops. In these cases, the levelling effect of the field dependency can no longer be ignored. The error made when using the approximation on the standard cable is shown in Figure 2.8. The absolute value of the error is calculated for the field near the conductor, and near the lead-sheath for different voltages and temperature drops. The error at the conductor is always larger than the error at the lead-sheath. The error for a temperature drop \( \Delta T=10^\circ C \) is the smallest as the field distribution is almost flat.

![Figure 2.8 Error in field calculation when using the approximation, equation (2.8), instead of equation (2.6).](image)

Resistance
As the conductivity of the insulation is temperature and field dependent, the total resistance of the cable depends on temperature and field too.
The total resistance per metre cable, taking into account both temperature and field dependency is given by

\[ R_{\text{total}} = \frac{\exp(-\alpha T_s)}{2\pi \sigma_0 R_o} \int_{R_i}^{R_o} \frac{r^{k-1}\exp(-\gamma E)}{R_i} dr, \]  

(2.10)

in which \( T_s \) is the temperature of the lead-sheath. This equation is derived in Appendix E. From this equation, it is seen that the total resistance of the cable depends exponentially on the absolute temperature of the cable. This equation can only be calculated numerically. Disregarding the effect of the field dependency by setting \( \gamma = 0 \), we can write the equation in a closed analytical form

\[ R_{\text{total}} = \frac{\exp(-\alpha T_s)}{2\pi \sigma_0 k} \left[ 1 - \left( \frac{R_i}{R_o} \right)^k \right]. \]  

(2.11)

But remember that this equation is an approximation!

To get an idea of the order of magnitude, the results of equation (2.10) are shown in Figure 2.9 using the dimensions of the standard cable (§2.2). It follows that the higher the voltage is, the lower will be the total resistance of the cable, provided that the temperature stays the same.

**OBSERVE:** Equations (2.10) and (2.11) represent the total resistance per metre cable.
Chapter 2  Electric Fields

Charge
Space charge will be present in the insulation due to the temperature and field dependencies. The space charge distribution in a cable may be calculated using [55]

\[ \rho = J \cdot \nabla \frac{\varepsilon}{\sigma} \]  

(2.12)

and

\[ J = \sigma E, \]  

(2.13)

in which \( J \) is the current density. This equation can be calculated using numerical methods only. The software as described under §2.2.2 has been used. Charge distributions in the standard cable at different temperature drops and at 450 kV are given in Figure 2.10. The highest charge densities are found near the conductor. However, the higher the temperature drop is, the more the charge will be pushed towards the lead-sheath. The charge distribution in the case that \( \Delta T = 0^\circ C \) is due to the field dependency of the insulation only. Observe that the polarity of the charge is of one sign only. As the insulation itself was neutral, this means that charge is injected from the conductor and/or the lead-sheath.

The total charge per metre cable (\( Q_p \)) is indicated in this figure as well. It has been calculated using

\[ Q_p = \int_{R_i}^{R_0} 2\pi r \rho dr. \]  

(2.14)
When the field dependency is disregarded, an approximation in calculating the space charge can be made. The calculation may be found in [55], the final result is written as

\[ \rho = \varepsilon k \frac{E}{r} \]  

(2.15)

Just as in the case of the field approximations, care has to be taken as the error may go up to 50%, especially for higher temperature drops and higher field strengths.

From this equation, the total charge per metre cable may also be written in a closed analytical form. Using equation (2.14) and approximation (2.15) we find

\[ Q_p = 2\pi \varepsilon k \int_{r_i}^{r_o} Edr = 2\pi \varepsilon k U. \]  

(2.16)

The error in the calculated total charge \( Q_p \) using equation (2.16) may now go up to 200%. Anyhow, from equation (2.16), we learn that the total charge in the insulation due to the temperature difference is proportional to the voltage \( U \) and to the temperature drop \( \Delta T \) (\( k \) is a function of \( \Delta T \)).

2.2.4 Stage III\(^a\) - After switching off the load

A special stage is introduced here: in stage III\(^a\), the voltage \( U \) remains constant but the load current \( I \) is switched off. The cable will cool down and the temperature drop will decrease to 0°C. As a result, the field distribution will gradually change from the inversed field back to the usual field where the highest field strength occurs near the conductor. The field in stage III\(^a\) is an intermediate field. The theory as described in §2.2.2 is applicable. For this reason, we do not go into detail concerning the fields during this stage.

The reason for introducing this special stage is that the cable is vulnerable during the cooling down. Partial discharges with an enhanced repetition rate will occur with a possible harmful effect on the cable. An elaborate description of these phenomena during stage III\(^a\) can be found in §3.3.2 and §3.4.
2.2.5 Stage IV - After switching off the voltage

In stage IV, the voltage is switched off. After a short time, determined by the cable capacitance and internal resistance of the voltage source, the external voltage is reduced to zero. In this study, the time constant $\tau_U$ of the decrease of the voltage was approximately 1 minute. The field inside the cable, however, may be present for a far longer time, due to the slow decrease of the space charge. The field remaining after switching off the voltage is a purely charge-induced field.

Three situations can be distinguished (see Figure 2.11).

![Diagram showing different situations in stage IV](image)

**Figure 2.11** Different situations in stage IV as defined in the text.

1. The cable was not loaded before switching the voltage off.
2. The cable was loaded before switching off the voltage. The load is *not* switched off.
3. The cable was loaded before switching off the voltage. The load is switched off as well.

If the cable was not loaded before (situation ①), the remaining field is not so high because the insulation contains hardly any space charge. Therefore, situation ① is not considered here.

Situations ② and ③ give similar decays of the field. In situation ③, the field takes some more time to diminish than it does in situation ②, as the temperature is decreasing due to switching off the load.
In the following, situation 2 is considered. A cable loaded previously may keep a considerable charge-induced field. As an example, the field distributions of the standard cable after switching off the voltage are shown in Figure 2.12. The voltage before switching off was 450 kV, whereas the cable is constantly loaded with a current such that the temperature drop $\Delta T$ is 15°C. The software introduced in §2.2.2 was used. The field marked with $t=0^−$ is the field just before switching off the voltage, whereas the field marked with $t=0^+$ is the field just after switching off the voltage. The other lines represent the field as it decreases in the course of time.

The field at $t=0^+$ just after the voltage has been switched off can be calculated according to

$$E(t=0^+) = E(t=0^-) - E_{AC},$$

(2.17)

in which $E_{AC}$ is the capacitive field given by equation (2.2) and $E(t=0^-)$ is the DC field just before switching off the voltage. The field $E(t=0^+)$ is then the field which is induced by the remaining space charge [55].

2.2.6 Stage V - At polarity reversal

It is known that high stresses may occur at the conductor immediately after reversing the polarity of an external voltage source. This is especially the case if the cable is loaded and there is a temperature gradient. The distortion of the field at polarity reversal is caused by the space charge of the loaded cable. The field just after the polarity reversal may be calculated in analogy with §2.2.5 as:

$$E(t=0^+) = E(t=0^-) - E_{AC},$$

(2.18)
where

\[ E_{AC} = \frac{2U}{r \ln \left( \frac{R_o}{R_i} \right)} \]  \hspace{1cm} (2.19)

\( E(t=0^-) \) is the field just before the polarity reversal and \( E(t=0^+) \) the field just after. As the voltage is quickly\(^3\) changed from \(+U\) to \(-U\), a swing \( E_{AC} \) in the electric field according to (2.19) occurs. This field is subtracted from the initial field.

Two examples are given in Figure 2.13: one in which the cable is not loaded and one in which the cable is loaded, thus resulting in a temperature drop of 15°C. The initial voltage was 450 kV. After the reversal it was -450 kV. The field at the conductor is the highest after a polarity reversal, whether the cable is loaded or not. The field at the conductor after a polarity reversal of a loaded cable is high (47.1 kV/mm in this case) compared to the normal fields in service.

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\(^3\) In actual converter stations, the polarity reversal takes a very short time. It may be done in several minutes or less than one minute. The test recommendations for HVDC submarine cables [22] demand a reversal within 2 minutes with a possible extension to a maximum of 10 minutes. The time constant \( \tau \) of a cable is generally far longer.
2.2 Fields at different stages

Obviously, the field at the conductor just after the reversal is largely affected by the temperature drop $\Delta T$. This has been calculated and is shown in Figure 2.14. Here the voltage was also reversed from +450 kV to -450 kV.

It can be concluded from this figure that the field at the conductor, immediately after the reversal, increases linearly with the temperature drop, whereas the field at the lead-sheath decreases linearly.

If the cable did not suffer from inversion at all, this large field increase would not occur. We now consider what measures should be taken to keep the field inversion as low as possible. In §2.2.3, it was stated that parameter $k$ describes the inversion. Keeping $k$ as low as possible results in small field inversions. We rewrite parameter $k$,

$$ k = \frac{\alpha \Delta T}{\ln \left( \frac{R_o}{R_i} \right)} = \frac{\alpha W_c \rho_{sh}}{2\pi}, $$

(2.20)

in which $W_c$ represents the heat losses in the conductor and $\rho_{sh}$ is the specific thermal resistivity of the insulation. The field inversion can be kept as low as possible in three ways:

1. By choosing an insulation material that has a low temperature dependency coefficient $\alpha$. To date, no usefull DC cable insulation material with a sufficiently low temperature dependency coefficient $\alpha$ has been developed.

2. By reducing the specific thermal resistance $\rho_{sh}$ of the insulation material. To date, no usefull DC cable insulation material with a sufficiently low thermal resistance has been developed.

3. By reducing the losses produced by the conductor. The losses are ohmic losses and depend on the current $I$, the electric resistivity of the conductor material $\rho_c$ and the conductor area $A$. However, the most often used conductor material is copper, which already has a low resistivity. The losses may be reduced by reducing the current $I$, which is not desirable. Increasing the conductor area will reduce the conductor losses,
however, the cable will become more expensive.

2.2.6 Stage VI - After polarity reversal

An intermediate field will be present after the polarity reversal. In this stage (VI), the field gradually changes from the field as calculated in section 2.2.5, to a stable field gained by the reversed voltage source (stage VII). The fields that are calculated and presented in this section were computed using the software introduced in §2.2.2.

![Figure 2.15](image1)  
**Figure 2.15** The charge density after a polarity reversal from +450 kV to -450 kV. The temperature drop \( \Delta T \) remained stable at 15°C. The temperature of the sheath was 35°C.

![Figure 2.16](image2)  
**Figure 2.16** The field distribution after a polarity reversal from +450 kV to -450 kV. The temperature drop \( \Delta T \) remained stable at 15°C. The temperature of the sheath was 35°C.

We concentrate on the case of a loaded cable, as the highest field strengths occur in that case. In §2.2.3 (Stable field), it was explained that the space charge caused by the non-linearity of the insulation was of one sign only: the same polarity as the external voltage. After a polarity reversal, the space charge must reverse too. This will happen gradually as shown in Figure 2.15. The charge distributions in this figure are a result of a reversal from +450 kV to -450 kV. The cable load is not changed, the temperature of the lead-sheath is kept constant at 35°C and the temperature drop at 15°C. In Figure 2.16, the corresponding change in the field is shown. The field strength at the conductor is initially very high, but it decays quickly.
2.2 Fields at different stages

Polarity reversals are severe conditions which, in the recommended tests for HVDC cables, play an important role [22]. It is expected that the ambient temperature has an influence on the decay of the high field strength immediately after a polarity reversal. It is important to know the extent to which the temperature affects the field, as it may make the test more severe.

First, the test as recommended by [22] is defined. Second, two possible situations are calculated and evaluated.

The polarity reversal as defined in the official recommendations [22] is rephrased below:

*The cable shall be submitted to a total of 30 daily loading cycles. One cycle consists of 8 hours heating, followed by 16 hours cooling. Starting with positive voltage, the voltage polarity shall be reversed every 4 hours and one reversal shall coincide with the cessation of loading current in every loading cycle. The test voltage shall be 1.5\(U_0\).*

![Figure 2.17](image1)

*Figure 2.17* The temperature of the lead-sheath and the conductor as a function of time as defined in the text. Situation 1.

![Figure 2.18](image2)

*Figure 2.18* The temperature of the lead-sheath and the conductor as a function of time as defined in the text. Situation 2.

The two calculated situations are (see Figures 2.17 and 2.18):

1. A polarity reversal test as defined at an ambient temperature of 20°C (Figure 2.17). The lead-sheath temperature after eight hours heating is 35°C, the conductor temperature is then 50°C. The thermal time constant

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4 The test recommendations [22] are under revision. In particular, the values of the test voltages will be changed. Here the values given in the "old" recommendations [22] are used.
was set to three hours. It simulates a land cable or a buried shallow-water cable. At the beginning of the test, the cable was in a stable thermal and electric situation. The voltage on the cable was $1.5 \times 450 = +675$ kV and after reversal -675 kV.

2 A polarity reversal test as defined at an ambient temperature of $4^\circ$C (Figure 2.18). The lead-sheath temperature is kept constant at $4^\circ$C. The temperature of the conductor after the eight hours heating is $19^\circ$C. The thermal time constant was set to three hours. It simulates an unburied deep-water cable. At the beginning of the test, the cable was in a stable thermal and electric situation. The voltage on the cable before reversal was $1.5 \times 450 = +675$ kV and after reversal -675 kV.

![Figure 2.19 The field at the conductor as a function of time during a polarity reversal test as recommended by [22]. Situation 1: high ambient temperatures. Situation 2: low ambient temperatures.](image)

The results of the calculations of situations 1 and 2 are represented in Figure 2.19. The figure shows the field strength at the conductor as a function of time. The high field, which is present immediately after the polarity reversal, decays more slowly for the cable in cold environment (situation 2) than for the cable in warm environment (situation 1).

It is concluded that testing a cable with polarity reversals and subjected to a low ambient temperature is a more severe test than that of a cable subjected to a high ambient temperature.

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5 The heating and cooling of the cable was modelled with one exponential function only. It would have been more correct to model the thermal resistances and thermal capacitances of all cable materials and to take into account the ambient parameters such as heat radiation, which would result in a series of exponential functions. This is far too complex and is not necessary to explain the effect of temperature on the field decay after a polarity reversal.
2.3 Effect of ohmic insulation loss

2.2.8 Stage VII - Stable after polarity reversal

After the intermediate field of stage VI, the field becomes stable in stage VII. The field is of opposite polarity to the field in stage III. All calculations made in stage III are valid for stage VII, but with an opposite sign:

\[ E_{vII} = -E_{III}. \]  \hspace{1cm} (2.21)

2.3 Effect of ohmic insulation losses

The leakage current \( I_0 \) in the insulation heats the insulation; this is caused by ohmic losses which are of the form

\[ w = \frac{I_0^2}{(2\pi r)^2 \sigma}, \]  \hspace{1cm} (2.22)

in which \( w \) is the power generated per unit volume and \( I_0 \) is the leakage current per metre cable. Normally, the power generated throughout the whole insulation per metre of cable is in the order of 1 mW, which is small compared to the 25 W per metre of cable which is generated by the conductor. These values are rough figures calculated at a moderate stress and ambient temperature.

The effect of the ohmic insulation losses may be greater at higher stresses and ambient temperatures. Consider the following. The leakage current will heat the insulation due to the ohmic insulation losses. Therefore, the temperature of the insulation will rise. The higher temperature will lead to an increase in the electrical conductivity. This higher conductivity causes a higher leakage current. However, the higher leakage current will in its turn heat the insulation. The process continues until either a balance is reached or an unstable situation occurs.\(^6\)

Thus, the electric field may be influenced to a larger extent than one would expect using equation (2.22).

In the following, the electric field distribution is calculated, taking into account the effect of the ohmic insulation losses. It can be calculated (Appendix D) that

\(^6\) The latter has been mentioned by [29].
the temperature drop $T_r - T_c$ at location $r$ inside the insulation due to the heating by the leakage current $I_o$ is given by

$$T_r - T_c = -\rho_{sh} I_o^2 \int_{r=R}^{r'} \left( \int_{r''}^{r'} \frac{dr''}{4\pi^2 (r''^2)^2 \sigma} \right) dr' , \quad (2.23)$$

in which $T_r$ is the temperature of the insulation at location $r$, $T_c$ is the temperature of the conductor, $\rho_{sh}$ is the specific thermal resistance of the insulation which is thought to be independent of temperature, and $\sigma$ is the electric conductivity which depends on the location in the insulation. This temperature drop comes in addition to the well-known temperature drop $\Delta T$ which is the result of the conductor losses.

Equation (2.23) may be used to calculate the electric field. The electric field distribution is calculated in an iterative way:

1. Calculate an initial field (this may be the field calculated with the equations in section 2.2.3).
2. Calculate the temperature distribution using equation (2.23).
3. Calculate the distribution of the electric conductivity.
4. Calculate the electric field distribution.
5. Calculate the leakage current $I_o$.

Repeat steps 2 to 5 until the field distribution does not change more than $10^{-2}$ kV/mm. It is possible that this equilibrium situation will not occur and the changes in field of following iterations become larger and larger. This is the instability mentioned in footnote 6.

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**Figure 2.20** Stable field distributions taking into account ohmic insulation loss for different temperatures of the lead-sheath $T_r$, $U=900$ kV.

**Figure 2.21** Field $E$, at the lead-sheath taking into account ohmic insulation loss as a function of the temperature of the lead-sheath $T_r$, $U=900$ kV.
2.3 Effect of ohmic insulation loss

The fields were calculated for the cable at $2U_0=900$ kV with a current of 1500 A flowing through the conductor of the standard cable. The calculations were done using different lead-sheath temperatures $T_s$ to investigate the effect of the ambient temperature. The thermal conductivity $\sigma_{th}$ was $0.17 \text{ Wm}^{-1}\text{°C}^{-1}$. The results are shown in Figure 2.20.

It is seen that the field is pushed still more towards the conductor, but for very high temperatures, $>70^\circ\text{C}$ only. This is shown in Figure 2.21 where the field $E_s$ at the lead-sheath is shown as a function of the temperature $T_s$ of the lead-sheath. For temperatures of the lead-sheath higher than $83^\circ\text{C}$, no solution exists and instability sets in.

As the leakage current $I_0$ is the parameter which causes the deformation of the field, we have a closer look at Figure 2.22. The relation between the leakage current $I_0$ and the temperature of the lead-sheath $T_s$ is exponential. This was expected, as the electric conductivity is exponentially proportional to the temperature.

However, several centigrades before instability, the leakage current $I_0$ is increasing more than exponentially (indicated by the curved arrow). The power $W_p$ generated by the insulation losses and the power $W_e$ generated by the conductor losses are shown in the same figure. It is seen that $W_p$ has the same exponential shape as the leakage current $I_0$. For the higher temperatures, the power $W_p$ takes values just as high as the average conductor losses $W_e$ or even more.

Figure 2.22 shows that at a temperature of the lead-sheath $T_s$ of $70^\circ\text{C}$, the power generated by the insulation is approx. $\frac{1}{3}$ of the power generated by the conductor ($W_p=0.3W_e$). The electric field distortion caused by the leakage current becomes important starting at this temperature of $70^\circ\text{C}$. It is, therefore, concluded that the insulation losses may not be disregarded in cases where $W_p \geq 0.3W_e$. 

![Figure 2.22 Leakage current per metre cable $I_0$ and power $W_p$ generated by the leakage current as a function of the temperature of the lead-sheath $T_s$. $W_e$ is the power generated by the conductor. $U=900$ kV.](image-url)
The conclusions are twofold.

1. The insulation losses can no longer be disregarded in the cases where \( W_p \geq 0.3 W_e \). This is the case for high lead-sheath temperatures (>70°C). The maximum operating temperature of mass-impregnated insulation, however, is about 55°C. The insulation losses may, therefore, be disregarded under normal service conditions concerning this type of cable.

Oil-filled cables, however, may be used at a much higher operating temperature. Consequently, the risk for a thermal breakdown during testing or under service conditions is present.

2. In laboratory situations and when evaluating new insulation materials at high temperatures, one should be aware of the effect. A risk of instability may then be present.

### 2.4 Voltage impulses superimposed on DC

An HVDC cable may suffer from switching and lightning transients. A cable in service experiences these transients superimposed on its own DC voltage. In the following, impulses superimposed on a DC voltage are considered, especially the impulses superimposed on a DC voltage of opposite polarity, to which the cable is most vulnerable [24, 8, 35, 70].

The definition of symbols is given first. \( U_{DC} \) is the DC working voltage, \( U_p \) is the resulting peak voltage if an impulse is superimposed on the existing DC voltage (see Figure 2.23).

The field at the event of an impulse can be calculated using

\[
E_p = E_{DC} + E_{AC},
\]

(2.24)

**Figure 2.23** Definition of voltages \( U_{DC} \) and \( U_p \).

where

\[
E_{AC} = \frac{U_p - U_{DC}}{\ln \left( \frac{R_o}{R_i} \right)}.
\]

(2.25)
Note that the capacitive field $E_{AC}$ is larger for superimposed impulses of opposite polarity ($|-U_p-U_{DC}|>|U_p-U_{DC}|$).

As an example, the field at the event of the impulse is calculated for the cable at +450 kV with a superimposed impulse of opposite polarity such that $U_p = -1000$ kV. The fields are calculated for an unloaded cable ($\Delta T=0$) and for a loaded cable ($\Delta T=15^\circ C$). The result is shown in Figure 2.24. The resulting field strength is the highest near the conductor, both for a loaded and an unloaded cable. The loaded cable suffers from a higher total field strength $E_p$ than the unloaded cable.

In the case of a superimposed impulse of the same polarity, the field strength at the conductor is always the highest for an unloaded cable, but may become higher at the lead-sheath for high DC voltages when loaded (not shown in the figure).

The field at the conductor $E_c$ in the event of a superimposed impulse is evaluated for several prestressing DC voltages $U_{DC}$ and temperature drops $\Delta T$ in Figure 2.25. The absolute value of the peak voltage $U_p$ was set to 1000 kV. The magnitude of the field at the conductor is decreasing with increasing DC prestress for impulses superimposed on a DC voltage of the same polarity. The magnitude of the field is increasing with increasing DC prestress for impulses superimposed on a DC voltage of opposite polarity. Higher
temperature drops $\Delta T$ increase the effect.

By comparing the field strengths in Figure 2.25, it is concluded that a test with an impulse superimposed on a DC voltage of opposite polarity (arrow $a$) leads to higher field strengths near the conductor than to a test done with an impulse of the same polarity (arrow $b$) as the DC voltage.

On top of this, the *breakdown field strength* is lower in the case of an impulse superimposed on a DC voltage of opposite polarity than an impulse superimposed on a voltage of the same polarity. This has been found by several authors for mass-impregnated paper cables [35, 8, 70] and for extruded cables [82, 68]. This has two reasons.

1. The capacitive field during the impulse, described by equation (2.25) is larger for the impulse superimposed on a DC voltage of opposite polarity than the capacitive field during a pulse superimposed on a DC voltage of the same polarity. In a mass-impregnated paper the butt-gaps are stressed mostly by this capacitive field as they have a lower permittivity $\varepsilon_r$ than the paper. This holds for oil-filled and gas-filled butt-gaps. The butt-gaps are the weakest points in the cable and will, therefore, suffer more from an impulse superimposed on a DC voltage of opposite polarity.

2. Mass-impregnated paper cables and extruded cables may contain space charge. In the case of a paper cable, homocharge will be accumulated in the paper layers adjacent to the conductor and lead-sheath as shown in Chapter 4. Extruded cables may contain homocharge as well. At the event of an superimposed impulse of opposite polarity, these homocharges increase the stress in the butt-gaps of a paper cable and the interfaces of an extruded cable.
3 Partial discharges in mass-impregnated DC cable

During cooling of a cable partial discharges may occur in the butt-gaps in the insulation of a DC paper cable. It is known that these discharges might harm the insulation and decrease the reliability of the cable. It is therefore important to understand the discharge behaviour of an HVDC cable.

No international standards exist which describe how to measure partial discharges under DC. Therefore, the experience of Fromm [32] and Shihab [91] has been used. Few publications exist on partial discharge in HVDC cables [7, 16, 34] and this work attempts to fill this gap by measuring partial discharges in HVDC cables with mass-impregnated paper.

The more important differences in mechanisms of partial discharges under AC and DC as well as the DC detection method are discussed in §3.1. The test setup is described in §3.2. The results of the partial discharge measurements during different stages, as defined in chapter 2, are presented in §3.3. Partial discharges, as measured immediately before breakdown, are treated in §3.4. The conclusions of this chapter are given in section 3.5.

3.1 Partial discharges

Partial discharges generate pulses of short duration, regardless of the type of voltage source: AC or DC [55]. Therefore, for DC discharges, similar detection techniques are used as those for AC. This is discussed in §3.1.3.

The observation techniques for discharges at DC, however, are different because of the absence of phase information; evidently, partial discharges at DC have no phase information. This is discussed in §3.1.4.
3.1.1 Discharges at AC voltage

Partial discharges under 50/60 Hz AC voltage occur because of the constantly fast-changing voltage \( dU/dt \gg 0 \). The partial discharges are energized by the capacitive field.

During some stages in a DC circuit the voltage changes fast enough to describe the discharge process as AC discharges. These stages are: during the increase of the voltage (stage I), during the decrease of the voltage (stage IV), and during a polarity reversal (stage V).

"Fast enough" means that the following condition must be fulfilled (see section 3.1.2 for the calculation):

\[
\left. \frac{dU}{dt} \right|_{AC} > \frac{U}{\tau_{DC}},
\] (3.1)

in which \( \tau \) is the time constant of the process of recharging of a void at DC voltage. The term \( dU/dt \) can, for instance, be the crest of the increasing voltage during stage I.

Necessary conditions for a discharge to occur are (See Figure 3.1 for the explanation of the symbols):

- The voltage across the void must exceed the minimum breakdown voltage \( U_{min} \).
- A starting electron must be present. It may be supplied by external radiation or by previous discharges. Once the minimal breakdown voltage \( U_{min} \) has been reached, a certain time has to be waited before the discharge starts. This statistical time lag \( t_L \) is neglected here, but this assumption does not affect the results.

When a discharge has occurred, the voltage across the void falls back to the residual voltage \( U_r \), that in most cases differs from zero. The residual voltage is not a constant [32]. In the following text, the residual voltage will be assumed constant. This assumption does not affect the results of this work.

The voltage across the void is called \( U_v \) and the asymptotic voltage across the void if it would not discharge is named \( U_s \). The process can be described satisfactorily by the well-known \( a,b,c \) scheme [55, 32] as shown in Figure 3.1.
3.1 Partial discharges

The a,b,c circuit as used to describe discharges during a changing voltage (stages I, IV and V). The residual voltage $U_r$ is assumed constant and the effect of a waiting time for a starting electron has not been taken into account in the figure for reasons of clarity.

The repetition rate of the discharges in the capacitive stage is approximately given by

$$n \approx \frac{b}{b+c} \frac{dU}{dt} \frac{1}{U_{\text{min}} - U_r} \approx \frac{b}{c} \frac{dU}{dt} \frac{1}{U_{\text{min}} - U_r}, \quad (3.2)$$

in which $b$ stands for the capacitance of the sample insulation in series with the void and $c$ denotes the capacitance of the void itself. The approximation is valid if the void capacitance $c$ is far larger than the series capacitance of the sample $b$, which is mostly the case for cables. As can be seen, the repetition rate increases with increasing steepness of the rising voltage $dU/dt$. This repetition rate is usually many times larger than that found in the later stages II and III. For this reason either no discharge detection is performed during this initial stage, or the results are evaluated in another way than in the later stages.

---

7 a stands for the capacitance of the healthy part of the insulation.
Another difference here is that the discharges at AC voltage are bipolar and the discharges at a rising DC voltage are unipolar.

3.1.2 Discharges at pure DC voltage

To describe the discharge behaviour after the DC voltage has reached its final value, the a,b,c circuit as shown in Figure 3.1 is no longer representative. As the voltage is now constant, the dielectric current has to be taken into account. Resistances parallel to the capacitances are added to the a,b,c diagram to represent these currents [55, 32]. This is shown in Figure 3.2.

![Diagram of the a,b,c circuit extended with leakage resistances](image)

**Figure 3.2** The a,b,c circuit extended with leakage resistances to be used in resistive or transition stages. \( U_c \) = the actual voltage over the void, \( U_s \) = the asymptotic voltage over the void if it would not discharge, \( U_r \) = the residual voltage, \( U_{\text{min}} \) = the minimum breakdown voltage of the void (if no time lag \( t_c \) occurs), \( t_R \) = the recovery time and \( t_L \) = the statistical time lag (neglected in this work).

Once a discharge has occurred, the void is recharged by two processes recurring at the same time (see Figure 3.3), although one of them may be dominant.
3.1 Partial discharges

First, the void will be recharged by the dielectric current $j_D$ of the sample. This current is represented by the resistance $R_b$ in the modified a,b,c circuit.

Second, the charge resulting from the discharge redistributes itself resulting in a current across the surface resistance of the void: $j_c$. This current is represented by the resistance $R_c$ in the modified a,b,c circuit.

![Figure 3.3 A void is recharged by the dielectric current as well as by a recharging current across the void surface.](image)

The time constant $\tau$ of the recharging process is given by

$$\tau = \frac{R_b R_c}{R_b + R_c} \text{(b+c)},$$

(3.3)

in which $R_c$ denotes the surface resistance of the void and $R_b$ the resistance of the dielectric in series with the void. Although both processes take part at the same time, one of them may be dominant.

Next, the repetition rate of the discharges is calculated. The time between two successive discharges is given by

$$\Delta t = t_R + t_L,$$

(3.4)

in which $t_R$ is the recovery time of a defect, this is the time needed for the voltage across the defect to rise again from the residual voltage $U_r$ to the minimum breakdown voltage $U_{min}$. The time $t_L$ stands for the statistical time lag describing the time that one has to wait for the appearance of a starting electron. The repetition rate of the discharges is the inverse of this time interval, according to $n = 1/\Delta t$.

The repetition rate, as calculated below, neglects the statistical time lag. Therefore, this repetition rate is a maximum value.
Fromm [32] calculated the recovery time \( t_R \) of a defect by

\[
    t_R = -\tau \ln \left( \frac{U_s - U_{\min}}{U_s - U_r} \right).
\]

(3.5)

Fromm found for DC that the residual voltage \( U_r \) was very close to the breakdown voltage \( U_{\min} \) of the void. With \( U_r = aU_{\min} \) he found that for PE samples under DC stress the value \( a \approx 0.995 \). Equation (3.5) is rewritten as

\[
    t_R = -\tau \ln \left( 1 - \frac{1}{U_s - U_r} \frac{U_{\min} - U_r}{U_s} \right).
\]

(3.6)

If \( U_s \gg U_r \), which is normally the case (at least a factor 10), this equation turns into

\[
    t_R = -\tau \ln \left( 1 - \frac{1}{U_s} \frac{U_{\min} - U_r}{U_s} \right).
\]

(3.7)

Remembering that

\[
    -\ln \left( 1 - \frac{1}{x} \right) = \frac{1}{x} + \frac{1}{2x^2} + \frac{1}{3x^3} + \ldots \approx \frac{1}{x},
\]

(3.8)

it follows (again if \( U_s \gg U_{\min} - U_r \)),

\[
    t_R = \tau \left( \frac{U_{\min} - U_r}{U_s} \right).
\]

(3.9)

The repetition rate \( n \) is the inverse of \( t_R \)

\[
    n = \frac{1}{\tau} \frac{U_s}{U_{\min} - U_r}.
\]

(3.10)

From this equation it follows that

(1) the repetition rate \( n \) at DC voltage is linearly proportional to the asymptotic voltage \( U_s \) across the void, which in its turn is proportional to the external voltage. This means: the higher the external voltage \( U \) is, the higher is the repetition rate.
(2) the repetition rate increases with decreasing breakdown voltage $U_{\text{min}}$ of a void.

(3) the closer the residual voltage $U_r$ is to the breakdown voltage $U_{\text{min}}$, the higher is the repetition rate.

In a cable we often speak in terms of field strength. Setting $U_r$ and $U_{\text{min}}$ in equation (3.10) constant, we may say

$$n \propto \frac{E}{\tau},$$

(3.11)

in which $E$ is the electric field strength at the site of the void. Thus the repetition rate is linearly proportional to the local field $E$ and decreases with the local time constant $\tau$. Brasher [16] calculated this equation for a perfect spherical void and came to the same conclusion.

At this stage we can calculate the repetition rate at DC voltage and compare it with the repetition rate at a fast changing voltage (as described in section 3.1.1). The repetition rate $n$ at a fast changing voltage is given by (see equation (3.2)):

$$n \approx \frac{b}{c} \frac{dU}{dt} \frac{1}{U_{\text{min}} - U_r},$$

whereas the repetition rate at DC voltage is given by (see equation (3.10)):

$$n \approx \frac{1}{\tau} \frac{b}{c} \frac{U}{U_{\text{min}} - U_r},$$

in which it has been used that $U_s = b/(b+c)$ $U \approx b/c$ $U$. Upon comparing both equations it is concluded that the repetition rates are equal if

$$\frac{dU}{dt} = \frac{U}{\tau},$$

in which the lefthand side of the equation stands for the case of the fast changing voltage and the right hand side stands for the DC voltage. The result of this calculation was used in the beginning of section 3.1.1 (equation (3.1)), defining how "fast" a fast changing voltage is.
3.1.3 Discharge detection

Discharges at DC have the same high frequency content as at AC voltage. The detection of discharges at DC voltage may therefore be made in the same way as at AC voltage. In Figure 3.4, a straight DC detection circuit is shown. The actual detector (circuit I) is exactly equal to an AC detection circuit. The observation unit (part II) is specific for DC detection, where the usual phase information is missing. A signal conditioner shapes the analog signal and transfers it to the computer. The computer has three functions: (1) it controls the signal conditioner and the analog-to-digital convertor, (2) it records and saves the discharge data, and (3) it manipulates the discharge data so that they may be represented in relevant types of graphs as presented in §3.1.4.

The discharges in the sample are of one polarity only, determined by the DC source polarity (the little black arrow in Figure 3.4). Any unwanted discharges occurring in the coupling capacitor $k$, the DC source, or any other place outside the sample, have the opposite polarity and can therefore easily be suppressed by polarity rejection (see the white arrows in the figure).

A better reduction of disturbances may be achieved if a balanced detection circuit is used. This type of circuit has been used in this thesis.

Detailed information about discharge detection, regarding part I in the figure can be found in [54, 57]. More information regarding the specific DC part of the detection (circuit II) can be found in [55, 32].
3.1.4 Graphical representation

The discharges at AC can be related to the phase of the voltage source. At DC only two basic quantities can be measured: the discharge magnitude \( q \) of each individual discharge and the time interval \( \Delta t \) between two successive discharges (see Figure 3.5). This information forms the basis for the graphical representation of the discharges.

Different ways of displaying these data are in use. The most common graphical representations are:

1. the discharge magnitude as a function of time: \( q(t) \),
2. the discharge repetition rate as a function of time: \( n(t) \), and
3. the discharge repetition rate as a function of discharge magnitude: \( n(q) \).

Other functions were also introduced by Fromm [32].

\( q(t) \)

Each recorded discharge \( q \) is displayed at a time axis according to its time of occurrence. An example is given in Figure 3.6. No discharges are detected below the minimum level \( q_{\text{det}} \). This value is adjustable (in this thesis \( q_{\text{det}} \) was normally set to 25 pC).

Figure 3.5 At DC, two basic quantities can be measured, the discharge magnitude \( q \) and the time between two discharges \( \Delta t \).

Figure 3.6 The \( q(t) \) graph, where the discharge magnitude is displayed against the time of occurrence.
\( n(t) \)

The number of discharges \( N \) are counted during a certain time \( t_w \). Discharges with a magnitude in a adjustable range \( q_{\text{min}} \) to \( q_{\text{max}} \) are counted only. The discharge repetition rate \( n \) is then defined by \( N/t_w \). The repetition rate is usually displayed in \text{min}^{-1}. The time window \( t_w \) is usually set to 1 minute, but may be larger or smaller if desired. An example of an \( n(t) \) graph is shown in Figure 3.7.

\( n(q) \)

The magnitude of the discharges is measured during a test period \( t_M \). After the test, the discharges are classified in magnitudes (\( q_i, q_{i+1}, \ldots \)). In each magnitude class, the repetition rate of the discharges \( n(q_i) = N(q_i)/t_M \) is computed and displayed in a graph like that in the left-hand part of Figure 3.8. No discharges smaller than the minimum detectable level \( q_{\text{det}} \) are displayed. Usually, the graph is inverted and shown as a \( q(n) \) graph as can be seen in the right-hand part of the figure.
3.2 Experimental methods

During this work, three cables were tested. One cable of type A and two cables of type B, each 15 metre in length. The cable of type A had an oval 400 mm² copper conductor (22.1/26.6 mm diameters) and a mass-impregnated paper-type insulation (12.1 mm thickness). Carbon paper was used as the first and the last layer of insulation. The cable was finished with a lead-sheath. The cables of type B had a round 400 mm² copper conductor (23.9 mm diameter) and a mass-impregnated paper-type insulation (15.6 mm thickness). Carbon paper was used as the first and the last layer of insulation. The cable was finished with a lead-sheath, a reinforcing tape and a PE sheath. Porcelain terminals were used, filled with a high viscous oil. Corona rings were placed on top of the terminals.

The tests were performed using a bridge-type detector as drawn in Figure 3.9. The noise rejection of a bridge circuit works best if the two samples $a$ and $a'$ are almost identical in terms of capacitance and losses. This goal was reached in two different ways.

1. The cable of type A was electrically split into two equal parts by partly removing the lead-sheath and the carbon paper in the middle.
2. A cable of type B was measured against a cable of type A.

Method (1) has the best noise rejection (rejection ratios of 1000 or higher have been reached). Method (2) has the advantage that the cable sheath does not have to be cut.

The complete cable was covered in a flexible, aluminium tube, which acts as a cage of Faraday around the sensing electrode. This tube was connected to earth. The terminals were electrically separated from the cable. Thus unwanted discharges from the terminals were not measured.

Two temperature sensors were placed on the lead-sheath of each cable. The sensors were connected to a recording unit, printing the temperature as a function of time.
The voltage source was of the Greinacher type. Its maximum voltage was plus or minus 600 kV with a maximum continuous current rating of 10 mA. For breakdown tests, another source was used with a maximum of plus or minus 1000 kV. A recorder registrated the voltage as a function of time.

The heating current was induced by a current transformer. The two ends of the cable conductor were connected in order to form a closed loop.

3.3 Discharges at different stages

The voltage $U$ and the load current $I$ may vary during the stages. As a result of this, the temperature distribution, the electric field, the internal pressure, the distribution of voids in the cable, the viscosity of the oil and the conduction will change too. These changing parameters will have their effect on the discharge behaviour of the cable.

Some cases may have an irreversible effect on the cable. An increasing load current $I$, for instance, will change the void distribution. Upon decreasing the current to its original value, the void distribution will usually not return to its original value. The mass-impregnated cable is physically never the same, it is a "living" cable.

In the following sections, the discharge behaviour of the cable is discussed for the stages II, III, III$^a$ and IV. Stages I, V and VI are not discussed.

Before entering the following sections, the definition of the repetition rate will be adapted to the cable. The repetition rate, of the discharges in one void only, is given by equation 3.11. In a cable, many voids may exist and they will be distributed unevenly; for instance, there may be more voids near the conductor than near the lead-sheath. The distribution of voids as a function of the radius $r$ is given by $D_r$. The total discharge repetition rate of a cable is then given by

$$n(t) \propto \sum \frac{1}{\tau_r(t)} E_r(t) D_r(t)$$  \hspace{1cm} (3.12) 

taking into account that different electric fields, time constants, and void concentrations may be present at different radial locations in the cable and may change in the course of time. It is assumed that the void distribution is independent of the axial position of the cable.
3.3 Discharges during different stages

3.3.1 Load current during stage II

In stage II, the external voltage $U$ has just reached its final value. We now consider the case that also the load current $I$ is just switched on, as depicted in Figure 3.10. The conductor will get heated and a temperature drop $\Delta T$ across the insulation will grow in the course of time. The result of having switched-on the voltage and the loading current is that the electric field $E$, the void distribution $D$, the internal pressure $p$, the viscosity $\eta$, and the conduction $\sigma$ change. After some time they will become stable.

The effect on the repetition rate $n$ is remarkable. It is discussed using a test result that is shown in Figure 3.10. Cable A has been submitted to a negative DC voltage of 300 kV and a current of 500 A. The ambient temperature was 19°C. In the figure, the increasing temperature of the lead-sheath is shown, together with the increasing repetition rate of the discharges. Moreover, it was observed that the distribution of the discharge magnitude remained fairly constant. Partial discharges were measured between 25 pC and 1 nC. Hardly any discharges occurred above 100 pC.

It can be seen from the figure that the repetition rate $n$ increases with increasing temperature of the lead-sheath $T_s$. The time constant of the repetition rate $\tau_n$, however, is larger than the time constant of the temperature $\tau_T$.

The explanation of the increasing repetition rate is as follows. Equation (3.12), describing the repetition rate of the discharges in the cable, is used. During the heating of the cable three processes take place.

(1) The repetition rate is proportional to the electric field according to equation (3.12). The electric field $E_s$ changes due to the changing temperature distribution (see also chapter 2). The field near the conductor diminishes by a
factor 2 at the most, whereas the field near the lead-sheath increases by the same factor, at the most. Therefore, the net effect is zero, unless the number of voids near the lead-sheath is higher than the number near the conductor. In that case the increase of the repetition rate can still not be more than a factor 2.

(2) The conductivity of the insulation changes with temperature. This has its effect on the local dielectric time constants \( \tau_r \). Stating \( 1/\tau_r = \sigma_r \), it follows that equation (3.12) may be written as

\[
n(t) = \sum \sigma_r(t) E_r(t) D_r(t),
\]

which can be written as

\[
n(t) = \sum \sigma_0 \exp(\alpha T_r(t)) E_r(t) D_r(t).
\]

The higher the temperature is, the higher is the conductivity of the insulation, and, therefore the higher is the repetition rate. The relation between the repetition rate is exponentially proportional to the temperature. The effect of the temperature \( T_r \) on the repetition rate \( n \) is therefore much larger than that of the electric field \( E_r \).

(3) As a third process, the void distribution \( D_r \) will change. With rising temperature, the oil in the insulation expands and the internal pressure increases. It is likely that the oil will fill some voids, thus decreasing the number of voids. This effect is therefore not likely to be responsible for the increase of the repetition rate.

The previous description was based on the observation that the repetition rate increased with increasing temperature. Although less frequently, it has also been observed that the repetition rate decreased with increasing temperature. This has been found in cases where the cable was used again after a long period of rest, and was subjected to just one heat cycle after that period. An explanation could be as follows. If the cable has rested for a long time and is subjected to one heat cycle only, the voids that remain in the insulation are not stable and may easily be closed by the expanding compound. In this case, the void distribution \( D_r \) decreases considerably with time. Now, the effect of the changing void distribution is dominant and the repetition rate may decrease with increasing temperature.
3.3.2 Stage III\textsuperscript{a} - After switching off the load

Stages I to VII are defined in chapter 2 as voltage stages. Stage III\textsuperscript{a} was defined as a special case of stage III, where the load current is switched off. In this stage, the load current \( I \) is decreased to zero within a few seconds. The voltage \( U \) remains at the same level. A typical graph of the discharge repetition rate during this stage is shown in Figure 3.11.

The graph shows the typical shape of the repetition rate \( n(t) \) in stage III\textsuperscript{a} in which two peaks appear: A and B [48, 73]. First, a peak (A) starting quickly after switching of the load. It may start after less than half a minute and reaches its maximum within 1 to 5 minutes.

Second, a peak (B) starting somewhat later, reaching its maximum within 2 to 2 hours and with a slowly diminishing tail which may last up to 10 hours. Peak B corresponds to the top of the smoothed line in Figure 3.11.

Peak A is seen as the response of pre-existing voids to a sudden pressure change near the conductor. Peak B is seen as the result of the generation of voids due to compound shrinkage. The mechanisms are explained below.

**Peak A**

First, the proposition of peak A being a result of pre-existing voids is explained, using Figure 3.12. A test was made after cable A had rested for 3 months. In this time, the cable had completely recovered. All voids were refilled by the oil from the termination that served as a reservoir. After this period of rest, two load cycles were given. In stages II and III of the first cycle no discharges above the detection level

![Figure 3.11 The \( n(t) \) graph during stage III\textsuperscript{a}. Two peaks may be recognized, peak A and B.](image)

![Figure 3.12 In the very first cycle after a period of rest, peak A did not appear and peak B did. In the next cycle both peaks appeared again.](image)
were measured, because of the lack of voids. Next, the load was switched off, thus entering stage III\textsuperscript{a}. Peak A was not observed in this case, however, peak B was. After cooling down, a second cycle was made. Now, discharges could be measured in the stages II and III. They were a result of voids generated in the previous cycle. After switching off the load for a second time, both peak A and peak B were observed. Peak A is assumed to be the response of the voids generated in the previous cycle.

![Diagram](image)

Figure 3.13 Pressure changes inside the insulation. Reference: M. Akke, B. Ekenstierna [30].

The quick rise of the repetition rate (peak A) is explained below. Before switching off the load current ($n = n_f$), the minimum breakdown voltage equals $U_{\text{min},1}$ and the residual voltage equals $U_{r,1}$\textsuperscript{8}. These values are stable. The voltage across avoid is always between these values as shown in Figure 3.15.

\textsuperscript{8} It is assumed here that the residual voltage $U_r$ is not equal to zero but is close to the breakdown voltage $U_{\text{min}}$ (see §3.1.2). If the residual voltage was equal to zero, no discharges due to the changing breakdown voltage would have occurred. Therefore, the observation favours the theory that the residual voltage $U_r$ is not zero, but lies close to the breakdown voltage $U_{\text{min}}$. 
Immediately after switching off the load, the temperature within the insulation changes. As a result of the changing temperature, the internal pressure distribution changes. The pressure distribution has been modeled by Akke [30] as shown in Figure 3.13. From the figure it can be seen that, especially near the conductor, the pressure changes quite quickly. When switching off the load, the pressure adjacent to the conductor suddenly drops within about 5 minutes. This period of pressure drop agrees well with the observed time during peak A. The sudden drop in pressure results in a change of the breakdown voltage in the Paschen curve\(^9\) (see Figure 3.14). The residual voltage changes too as shown in Figure 3.15.

The pressure near the conductor can quickly change as much as from 3 Bars to less than 1 Bar. According to the Paschen curve for air, the minimum breakdown voltage \(U_{\text{min}}\) of an actual butt gap of height 100\(\mu\)m will change from 1.9 kV (3 Bars) down to 0.75 kV (0.8 Bar). During this decrease in breakdown voltage, the void will discharge several times. The decreasing minimum breakdown voltage \(U_{\text{min}}\) and residual voltage \(U\), force the voids to discharge earlier than if they would have remained the same (see Figure 3.15). We observe the high value of the repetition rate \(n=n_2\) and this rate is named peak A.

\(^9\) The Paschen curve is normally used in the case of Townsend discharges. At DC voltage, Townsend discharges dominate over streamer discharges [32]. The minimum breakdown voltage \(U_{\text{min}}\) in air according to Paschen is given by

\[
U_i = \frac{Bpd}{\ln \left( \frac{Apd}{\ln \left(1 + \frac{1}{\Gamma} \right)} \right)},
\]

in which \(A=14.6\ \text{cm}^{-1}\text{Torr}^{-1}\), \(B=365\ \text{V cm}^{-1}\ \text{Torr}^{-1}\), \(\Gamma=0.01\), \(p\) is the pressure in Torr and \(d\) is the height of the void in cm. Paschen's curve is valid for limited values of \(pd\) only [72].
After the pressure change, the repetition rate \( n \) becomes stable at a new level: \( n_3 \) which lies in the same order of magnitude as \( n_1 \).

Summarized: peak A is a result of pre-existing voids adjacent to the conductor which discharge due to the sudden pressure drop caused by switching off the load.

**Figure 3.15** The minimum breakdown voltage \( U_{\text{min}} \) and residual voltage \( U_r \) before, during and after the pressure drop. The discharge repetition rate, \( n_2 \), during the pressure change is much higher than the repetition rates, \( n_1 \) and \( n_3 \), before and after the pressure change.

**Peak B**

This peak will be shown to be the result of the increasing number of voids. As the temperature decreases as a result of switching off the load, the compound decreases in volume. The lead-sheath, however, stays at the same diameter and does not shrink. The space between the lead-sheath and the conductor is no longer filled completely. Voids will grow, mainly located in the butt-gaps of the insulation. As the number of voids grows, more discharges will occur. The repetition rate will increase due to this effect.

After a while, as the temperature is decreasing, the conductivity of the insulation will decrease. Therefore, after the starting increase, the repetition rate will decrease as observed.

The observations of the changing repetition rate are now modelled. Starting from equation (3.12), and disregarding the effect of the changing electric field, we start with

\[
n(t) = \sum_{r} \frac{D_r(t)}{\tau_r(t)}, \tag{3.15}
\]

in which \( D_r \) stands for the void distribution as a function of the radial location.
3.3 Discharges during different stages

Using $1/\tau_r = \sigma_r$ and disregarding the dependence of location, it follows that

$$n(t) = D(t) \sigma_r(t),$$  \hspace{1cm} (3.16)

in which $\sigma_r$ stands for the conductivity of the insulation near the lead sheath. This location near the lead-sheath is arbitrary, any location inside the insulation could have been taken as well. The conductivity may be calculated (again disregarding the field dependency) using

$$\sigma_L(t) = \sigma_0 \exp[\alpha T_s(t)],$$  \hspace{1cm} (3.17)

with

$$T_s(t) = (T_s - T_{amb}) \exp\left(-\frac{t}{\tau_T}\right) + T_{amb},$$  \hspace{1cm} (3.18)

in which $T_s$ is the temperature of the lead-sheath before switching off the load, $T_{amb}$ is the ambient temperature and $\tau_T$ is the time constant of cooling.

The number of voids is increasing, starting from a number of voids already present, $D_{before}$, and ending with $D_{after}$. As the change of temperature and the change in internal pressure follow approximately exponential laws, the increasing void number is assumed to follow an exponential law too, with time constant $\tau_D$,

$$D(t) = (D_{after} - D_{before}) \left[1 - \exp\left(-\frac{t}{\tau_D}\right)\right] + D_{before}.$$  \hspace{1cm} (3.19)

This model (equations (3.17) - (3.19)) has been computed and the results are shown in Figure 3.16. On the x-axis the time starting at load switch-off is shown. The y-axis shows the repetition rate $n_B$ during peak B normalized on the repetition rate $n_0$ just before switching off the load. The time constant $\tau_D$ of the void growth is chosen equal to the time constant of the changing temperature $\tau_T$. The calculation was

Figure 3.16 The repetition rate during stage III peak B ($n_B$) normalized on the repetition rate of stage III ($n_0$) as computed with the model.
performed using different values of generated number of voids, ranging from $D_{\text{after}} = 10D_{\text{before}}$ to $D_{\text{after}} = 70D_{\text{before}}$.

The time needed for the repetition rate to grow to a maximum according to the model is approx. 60 minutes. In practice, values ranging from 60 to 120 minutes have been found.

Values of $n_B/n_0$ ranging from 2.4 to 15 have been found according to the model. In actual cases, values of 3 to 15 have been found.

As this simple model predicts the behaviour of the repetition rate quite well, it is concluded that peak B is indeed the result of the void growth due to the contracting compound during cooling down of the cable.

3.3.3 Stage IV - After switching off the voltage

If the voltage $U$ across the cable is removed, it will decay with a time constant $\tau_U$ that is determined by the cable capacitance and the internal resistance of the voltage source, following the upper part of Figure 3.17. In the present work, this time constant was approximately one minute.

The bottom part of Figure 3.17 shows the observed repetition rate while the voltage is decreasing. It has been observed that discharges start not earlier than after the external voltage $U$ decreased by a certain value $\Delta U$. This value $\Delta U$ was 60 kV for the cable tested in this study.
Another observation is that this value $\Delta U$ is independent of the voltage $U$ before switching off. This is shown in Figure 3.18. The x-axis shows the voltage $U$ before switching it off; the y-axis shows the value of $\Delta U$.

![Figure 3.18](image)

**Figure 3.18** The value of $\Delta U$ is independent of the external voltage $U$.

**Figure 3.19** Discharges start after the external voltage $U$ is lowered over a value $\Delta U$.

The explanation is as follows (see Figure 3.19). At the moment of switching off the voltage $U$, the voltage $U_c$ across the voids in the cable has a value between the minimum breakdown voltage $U_{\text{min}}$ and the residual voltage $U_r$. When the external voltage $U$ is decreasing, so is the voltage across a void $U_c$. The voltage $U_c$ follows the external voltage according to $U_c = \frac{b}{c} U$. During this time, the voids cannot discharge as the voltage $U_c$ becomes less than the minimum breakdown voltage $U_{\text{min}}$. The voltage $U_c$ decreases until it reaches the opposite breakdown voltage $-U_{\text{min}}$. From here on the discharges start. The decrease of $U_c$ from $+U_{\text{min}}$ to $-U_{\text{min}}$ corresponds to the decrease of the external voltage $U$ by an amount of $\Delta U$.

We now calculate the voltage across the void due to the change of the external voltage $\Delta U$. The time constant $\tau_U$ of the decrease of the external voltage is much smaller than the time constant of recharging. Therefore, we may ignore the resistances in the modified a,b,c scheme and handle the case as if it were a capacitive problem. The voltage across the void $U_c$ is now

$$U_c(t) \approx \frac{b}{c} U(t).$$

(3.20)
The change of the external voltage is now related to the change of the voltage across the void from \(+U_c\) to \(-U_c\),

\[2U_{\text{min}} = \frac{b}{c} \Delta U.\] (3.21)

For the cable used here, the capacitance \(b\) per length of cable is 0.13 nF/m. For an air-filled void \(c\) adjacent to the conductor of height 100 \(\mu\)m, the capacitance per length is 6.3 nF/m. Thus, for an external voltage change of 60 kV, the voltage across a void adjacent to the conductor changes 0.13/6.3 \times 60 = 1.2 kV. The minimum breakdown voltage is then 1.2/2 = 0.6 kV (see equation (3.21)). The minimum breakdown voltage for such a void is according to Paschen: 0.9 kV. Within the uncertainties of this test, this is a reasonable agreement.

As the cable is cylindrical, voids of the same height which are next to the lead-sheath have higher capacitances. The void capacitance \(c\) for a void adjacent to the lead-sheath equals 10.8 nF/m. The external voltage \(U\) would have to decrease 91 kV to let this void discharge according to Paschen. It is concluded that voids further away from the conductor will discharge later than voids next to the conductor.

**Figure 3.20** The characteristic picture of the repetition rate of a previously heavily loaded cable on a long time scale.

**Figure 3.21** The characteristic picture of the repetition rate of a previously lightly loaded cable on a long time scale.

Figures 3.20 and 3.21 show two typical \(n(t)\) pictures on a larger time scale. The tests were started directly after the external voltage \(U\) began to decrease. The left figure is an example of stage IV of a previously heavily loaded cable. The right figure is an example of stage IV of a previously lightly loaded cable. The time scale is too large to view the earlier-described effect of a delayed onset of discharges.
3.3 Discharges during different stages

The $n(t)$ graph given in Figure 3.20 starts with a high repetition rate. It decreases with time at a rate quite equal to the rate of decrease of the external voltage $U$. As stage IV is a capacitive stage, equation (3.2) for the repetition rate $n$ may be used here. This equation states that the repetition rate is proportional to the external voltage change. The shape of the measured $n(t)$ graph is indeed governed by the decreasing voltage $U(t)$.

Figure 3.21 (previously lightly loaded cable) shows a different behaviour. In the first seconds, there is a high amount of discharges (peak I), after which the repetition rate decreases quickly. This sharp decrease is not well understood. The same behaviour as described above was expected. After that, a second increase (peak II), lasting somewhat longer, was found. This behaviour is not well understood either, but can be explained as follows. The peak may be due to released space charges in the paper layers adjacent to the conductor. The charges may act as a source of electrons to the voids near the conductor. As seen in Chapter 4, space charges will be kept inside the paper layers adjacent to the carbon paper. When the voltage across the paper is removed, these charges will be released. This process of releasing is described by two time constants. The first time constant was found to be in the order of one minute, the second time constant in the order of half an hour or more. The onset of the second peak in the $n(t)$ graph roughly equals the first time constant of this charge release. Therefore, the second peak in the $n(t)$ graph might be due to the release of space charges in the paper layers adjacent to carbon paper (i.e. the conductor).

This peak due to released space charge was not seen in the case of a heavily loaded cable. This may be understood by remembering that a heavily loaded cable will have many voids throughout the whole insulation. Therefore, the effect of the released space charge is screened by the large number of discharges in the rest of the insulation.
3.4 Discharges before breakdown

Cable B was subjected to a breakdown test. The test was made in the following way (see Figure 3.22).

- Start of the test with a voltage \( U \) (not \( U_d \)) and a load current \( I \). This loading lasted for 48 hours to be sure of a stable field and temperature distribution. The temperature of the lead-sheath was 37°C and the temperature of the conductor was 43°C, both in the stable situation.

1. The current was shut off. This period of off-load lasted for 12 hours.

2. The current was raised to its original value \( I \). The voltage was increased by a step \( \Delta U \) which was about 10-15% of the initial voltage \( U \). The new load condition lasted for 48 hours.

- Steps 1 and 2 were repeated until breakdown of the cable occurred.
- Partial discharges were measured during each phase.

During current-off (stage III) the discharges were the most severe. This was expected as this is the stage where the voids are formed. During, these stages the \( n(t) \) graphs had a common appearance as shown in Figure 3.11. As the voltage became higher, bursts of nanoCoulomb discharges appeared superimposed on the graph as in Figure 3.11. The repetition rate per class of discharge magnitude is shown for each cycle in Figure 3.23. As can be seen from this figure, discharges larger than 1 nC appeared during the second cycle, but quite infrequently. The fourth cycle shows a huge amount of large discharges, whereas in the fifth cycle they have disappeared again. Two hours after current switch-off in the fifth cycle, the cable broke down. It is most likely that most harm was done to the insulation in the fourth cycle, where many discharges with a magnitude of 1 nC and higher occurred.
3.5 Conclusions

After dissecting the cable, it appeared that carbon (the thick lines in Figure 3.24) had been formed adjacent to butt-gaps. This is understandable as the field is pushed away from an air-filled butt-gap that just had broken down. As a result, a high tangential field $E_{tan}$ is present next to the butt-gap between the paper layers. High tangential field concentrations between two paper layers may lead to discharges along these paper surfaces, preferably at a weak spot in the insulation. Surface discharges may have a magnitude in the order of nanoCoulombs [55, 32].

![Figure 3.24](image)

The energy of these surface discharges burns the paper surfaces to carbon. The tangential field strength adjacent to the next unharmed butt-gap increases and the same process starts there. As more butt-gaps get involved, a short-circuit path may be formed as shown by the arrow in the figure. The process will proceed until the effective insulation thickness is reduced to an effect that a total breakdown of the remaining insulation takes place. The final part of the breakdown path will be perpendicular to the paper layers.

The breakdown path of an AC insulation is often of the zig-zag form, leading to a typical tree structure. The breakdown path in the DC insulation, however, hardly showed a zig-zag form, but had a shape as shown by the arrow in Figure 3.24.

3.5 Conclusions

Concerning the measurement of partial discharges in a cable with mass-impregnated paper insulation, the following conclusions are drawn:

1. Immediately after switching off a load (stage III°) the internal pressure adjacent to the conductor drops a few Bars. As a result, pre-existing voids adjacent to the conductor discharge. The discharges last as long as the fast pressure drop occurs.
2. Approximately half an hour after switching off a load (stage III°), voids are generated due to contraction of the compound. This leads to an increase in the repetition rate with a maximum that occurs 1 to 2 hours after switching off the load. After this, the repetition rate will decrease due to the decreasing temperature.

3. In stage IV, the voltage is switched off. Due to the internal resistance of the source, the voltage decreases gradually. Discharge activity starts only after the external voltage has decreased a certain value $\Delta U$ (which was 60 kV for the cables in this work). This effect is explained by the fact that the voltage across the voids has to change from $+U_{\text{min}}$ to $-U_{\text{min}}$. When the discharge activity starts, the repetition rate during this stage is far higher than during stage II, III or III°.

4. The rate of decrease of the external voltage during stage IV determines the repetition rate of discharges of a previous heavily loaded cable.

5. NanoCoulomb discharges are considered to be detrimental to the cable.

6. It is highly probable that nanoCoulomb discharges represent surface discharges between successive paper layers adjacent to butt-gaps.
4.1 Space charge detection

In this chapter space charge formation in mass impregnated paper is discussed. Section 4.1 gives an elaborate description of the space charge measuring method used in this thesis. In §4.2, the preparation of the samples and the measuring protocol are presented. The test results are discussed in §4.3. The chapter ends with conclusions in §4.4.

4.1 Space charge detection

Space charge inside an insulator distorts the electric field. For this reason, it is important to know the magnitude and location of the space charge. With this knowledge, the "exact" electric field can be calculated using Gauss' law, which is evaluated in an one-dimensional form in equation (4.5). In earlier days, destructive methods to measure space charge were used, for instance, using a field mill or a capacitive probe [55, 49, 44]. These methods are, in fact, surface charge measurements: the sample was cut into slices to arrive at the site of the charge.

The disadvantage of destructing the sample has been overcome by the use of a new generation of space charge measurement methods. All these methods use a common principle (see Figure 4.1). An

Figure 4.1 Non-destructive space charge measurement.
externally applied physical quantity $\Phi_1$ interacts with the charge inside the sample. The charge in its turn interacts with, or generates a second physical quantity $\Phi_2$ that can be externally measured. The physical quantities differ per method; they might be pressure, temperature, electric voltage or current. A short description of the methods is given below.

1. The first method that was used was the Thermal Shock Method (sometimes referred to as Thermal Step Method) TSM [44, 95]. First, two conducting electrodes are deposited, one at each side of a dielectric sample. One side of the sample is exposed to a negative temperature step, which is the activating physical quantity $\Phi_1$. This temperature step diffuses through the sample and will, on arrival, slightly displace the internal space charges relative to the electrodes. This relative displacement results in a simultaneous change of the induced electrode charges, which can be measured as an electric signal (the measurable quantity $\Phi_2$). The diffusion of the heat through the sample can be computed. Together with the measured electric signal, the original space charge distribution can be calculated using deconvolution techniques.

2. Other methods use a very short pressure pulse as an external activator $\Phi_1$. The pulse travels as an acoustic wave through the sample; it displaces the space charges, which in turn change the electrode charges. Again, this results in a measurable electric signal in the external circuit. Methods of this type are named PWP (Pressure Wave Propagation method, [55, 44, 36]), PPP (Piezoelectrically Generated Pressure Pulse method) and LIPP (Laser-Induced Pressure Pulse method, [55, 44, 61]). They differ only in the method of generating the pressure pulse.

3. The method used in this thesis is called PEA, Piezo Electro-Acoustic method, sometimes referred to as ESAW (Electrically Stimulated Acoustic Wave method). This method uses an electric pulse as the activating physical quantity $\Phi_1$ and acoustic waves as a measurable physical quantity $\Phi_2$. Therefore, the PEA method can be seen as the counterpart of the PWP, PPP and LIPP methods [65].

Table 4.1 summarizes the various methods.
4.1 Space charge detection

<table>
<thead>
<tr>
<th>Measurement method</th>
<th>Activating quantity</th>
<th>Measurable quantity</th>
</tr>
</thead>
<tbody>
<tr>
<td>TSM</td>
<td>temperature</td>
<td>voltage/current</td>
</tr>
<tr>
<td>PWP</td>
<td>pressure</td>
<td>voltage/current</td>
</tr>
<tr>
<td>PPP</td>
<td>pressure</td>
<td>voltage/current</td>
</tr>
<tr>
<td>LIPP</td>
<td>pressure</td>
<td>voltage/current</td>
</tr>
<tr>
<td>PEA (ESA)</td>
<td>voltage</td>
<td>pressure</td>
</tr>
</tbody>
</table>

Table 4.1

4.1.1 Pulsed Electro-Acoustic method

The Pulsed Electro-Acoustic measurement method was developed by Prof. T. Takada and Dr. Cooke in close cooperation [69, 41, 92, 62, 65, 66, 67, 47, 46]. The principle of measuring is as follows (a more detailed description can be found in Appendix A).

A sample is put between two aluminium electrodes $E_{l1}$ and $E_{l2}$ (Figure 4.1). A DC source is present in order to generate space charge. During a measurement, a very short, high voltage pulse is put across the sample. When this electric pulse is present, the resulting electric field acts on the space charges inside the sample. Due to this field, the space charges and charges at the electrodes experience an electrostatic force.

The force is of short duration and travels as two pressure waves in both directions, to $E_{l1}$ and to $E_{l2}$. We follow the waves in the direction of $E_{l2}$. At first, the wave is transferred to the material of $E_{l2}$. This electrode has the function of delaying the acoustical wave until its arrival at a piezoelectrical sensor. The delay is necessary, because of the interference of the electromagnetical noise caused by the firing of the electrical pulse. Leaving $E_{l2}$, the wave is transferred to the piezoelectric PVDF (Polyvinylidene) sensor,
which converts the pressure into an electrical signal. After amplification, the signal is fed into an oscilloscope, and from there into a computer. The computer stores the signal and does some signal shaping and calibration, described in Appendix A. A typical signal may now look like the one shown in Figure 4.2. The electrode charges and the space charge inside the sample can clearly be distinguished. The original signal is a time-dependent signal. By using relation \( \rho(t) = \rho(s = v_{\text{sound sample}} \times t) = \rho(s) \), the signal is made space dependent. After leaving the sensor, the waves are transferred to a backing of acoustical materials. This has the function of attenuating the wave and delaying the reflections at the final interface.

The waves that travel in the direction of \( El \) are first reflected at \( El \), and then follow the same acoustical path as previously described. The system measures the electrode surface charges \( \sigma_1 \) and \( \sigma_2 \) as well as the internal space charge \( \rho \).

### 4.2 Experimental method

This chapter describes the type of sample material that is used, as well as its preparation and handling (§4.2.1). The measuring protocol is explained in §4.2.2.

#### 4.2.1 Sample material and sample preparation

The electrical insulation of the cable considered in this thesis is mass-impregnated paper. As explained in the introduction, this type of insulation is used most for HVDC cables. It is known that cables that use this type of insulation give satisfactory performance. The good performance might, among other things, have a relation to the space charge behaviour inside the paper insulation. Some authors [73] have suggested that there is no space charge at all, whereas others suggest that there is [51]. Kreuger [55] and Oudin [80] proved that, according to the Maxwell equations, there must be space charge inside the insulation at macroscopic scale if there is a temperature drop across
the insulation. Apart from these propositions, there is no published evidence of the existence or non-existence of space charge inside a paper-insulated cable. The space charge distribution inside such insulation has therefore been thoroughly investigated by the author.

It is important to stress that the space charge distributions discussed here were measured on single paper layer samples and not in a full-sized cable. There is a good reason for this. It is known that the acoustical damping inside mass-impregnated paper layers is quite high, about 0.6 to 0.8 times per 100μm for 10 ns pulses, which is the thickness of one paper layer. In a full-sized cable with approximately 18 mm insulation, this would mean an attenuation varying from $10^{-16}$ to $10^{-40}$ for charges that are 18 mm removed from the sensor. It is currently impossible to measure these heavily attenuated signals.

However, measures were taken to ensure that the paper samples were insofar as possible after preparation in the same condition as full-sized cable insulation. Details will be given later on.

**Paper and oil types**

There are different types of mass-impregnated papers in use as insulation material for both DC and AC cables. Important properties of cable paper are: thickness [μm], density [g/cm³], and air impermeability [Gurley’s]. Important properties for cable oil are kinematic viscosity [mm²/s] and specific electrical resistance [Ωm]. Typical values of the properties of the cable papers and oils used are given in Table 4.2 and Table 4.3.

<table>
<thead>
<tr>
<th>Paper type</th>
<th>Air impermeability [Gurley’s]</th>
<th>Density [g/cm³]</th>
<th>Thickness [μm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>6000-14000</td>
<td>940-1000</td>
<td>95-105</td>
</tr>
<tr>
<td>II</td>
<td>400-900</td>
<td>790-840</td>
<td>95-105</td>
</tr>
<tr>
<td>III</td>
<td>60-200</td>
<td>720-770</td>
<td>150-165</td>
</tr>
<tr>
<td>IV</td>
<td>400-900</td>
<td>750-800</td>
<td>115-125</td>
</tr>
<tr>
<td>carbon paper [105 Ωm]</td>
<td>300-700</td>
<td>850-950</td>
<td>95-105</td>
</tr>
</tbody>
</table>

Table 4.2. The thickness and density were measured according to the SCAN-P7 standard, the air impermeability according to the SCAN-P19 standard.
OIL PROPERTIES

<table>
<thead>
<tr>
<th>Oil type</th>
<th>Kinematic viscosity [mm²/s]</th>
<th>Electrical resistance [TΩm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>7400</td>
<td>350</td>
</tr>
<tr>
<td>II</td>
<td>4500</td>
<td>16</td>
</tr>
<tr>
<td>III</td>
<td>4.2</td>
<td>220</td>
</tr>
</tbody>
</table>

Table 4.3. The kinematic viscosity was measured according to the IEC 296A standard, and the electrical resistivity was measured according to the IEC 247 standard. The electrical resistances were measured at 20°C. The kinematic viscosities were measured at 40°C; at 20°C the oils of type I and II get too thick. Type III is a thin oil used for oil pressure cables.

Drying and impregnation

The samples were prepared such that it reflected the production of a full-sized DC paper cable. Starting from a fixed conductor, the production steps of a full-sized cable are: drying of the paper rolls, lapping of the dry paper insulation onto the conductor, vacuum drying of the full-sized paper-lapped cable, impregnating of the cable under hydrostatic pressure, natural cooling. From here on, the cable is lead sheathed and finished by applying the outer layers. Drying the paper is necessary, to remove the water that is held on the surfaces of the paper, and that is absorbed between the cellulose fibres. The electrical properties of paper are adversely affected by a high water content [71, 10, 88]. Care must be taken not to dry at a temperature that is too high (> 120°C), because of the decomposition of the chemically bonded water [10, 88].

The various samples were prepared in a similar process. The dimensions of the paper before treatment were 40 cm x 6 cm. The paper was dried under vacuum at 120°C for 90 hours. After the drying, the paper was impregnated at 120°C for 24 hours at atmospheric pressure with one of the oils listed in Table 4.3. The use of elevated pressure was not necessary, because of the small dimensions of the paper compared to a full size cable. After natural cooling, the samples were put in a cleaned glass bottle. The bottle was completely filled with oil, in order to totally immerse the paper in oil. The bottle was closed with a plastic cover. As an extra precaution against any moisture diffusing into the bottle, the bottle was wrapped in aluminium foil.
Handling

Any contamination of foreign chemicals or particles on the impregnated paper samples could affect the space charge behaviour. Therefore, in such tests, care must be taken to avoid contact with chemicals that could be present on human fingers, laboratory tools, etc. Below, is an explanation per point of how each test was prepared.

- The sensor area at \( E_{I_2} \) and the high voltage electrode \( E_{I_1} \) were cleaned, first by using a degreasing fluid called Nebol, second by using a 96% ethanol solution, and, finally, by using a paper tissue. Further every laboratory tool that could contact the sample or sensor area was cleaned similarly.
- A bottle containing the required type of paper was chosen, and a square sample (dimensions at least 2 x 2 cm) was cut with a clean pair of scissors.
- The sample was placed in the sensor area of electrode \( E_{I_2} \).
- The high voltage electrode \( E_{I_1} \) was then placed on top of the sample (see Figure A.1).

The time span from opening the sample bottle to the positioning of the high voltage electrode \( E_{I_1} \) on top of the sample was restricted to a minimum (± 1/2 min.), thus limiting the time that the sample was exposed to the open air.

- To prevent any possible diffusion of moisture in the sample, a PMMA box was put over the complete system. Silica gel inside this box will absorb any moisture present.

In AC technology, it is a well-known fact that the exposure of a piece of cable paper to open air affects the \( \tan \delta \) properties of the paper. This is explained by the adsorption of the moisture in the air by the paper sample. Moisture will affect the conductivity [88, 10, 51], and in general, the electrical properties of the paper. Therefore, it may affect the space charge distribution inside paper as well. For this reason it was checked whether the sample does absorb any amount of moisture during a measurement. This was done by measuring the current profile (current versus time, \( I-t \) graph) of a sample consisting of paper type I and oil type I. The paper sample of one layer thick was placed in a current-measuring device with guard electrode, the current was measured for a duration of at least 3 hours using a DC voltage of 5 kV. The sample was then transferred to the electro-acoustic system, and the high voltage electrode \( E_{I_1} \) was
placed on top of it. No DC or pulse voltage was applied. After 24 hours, the sample was transferred back to the current-measuring device and the \( I-t \) profile was measured again. The \( I-t \) graph of the virgin sample was compared with the graph of the exposed sample, see Figure 4.3.

As can be seen from the figure, the final value of the current is the same for the virgin sample and for the 24-hour sample. Also the complete current profiles of the virgin and the 24 hours sample are almost the same. From this, we can conclude that no considerable amount of water is absorbed during a 24-hour period in the electro-acoustic system (one test takes 24 to 48 hours).

This is understandable because the contact area of the edges of the paper sample with the air while positioned in the system is very small (±5 mm\(^2\)), see Figure 4.4. Moreover, the diffusion of moisture into the oil and paper sample proceeds very slowly, because of the hydrophobe character of the cable oils.

**Figure 4.3** Current versus time graph of a virgin and an exposed paper sample.

**Figure 4.4** Open air contact area of a sample in the electro-acoustic system. Contact area = \( \pi dh \).

### 4.2.2 Measurement protocol

Space charge distributions can be measured in two ways: with the DC voltage \( U_{dc} \) on, and with the DC voltage off (see Figure 4.1). During the test procedure, one measures the internal space charge together with the electrode charges \( \sigma_1 \) and \( \sigma_2 \).

In the case of a voltage-on test, the electrode charges consist of two types. The first type is induced by the space charge in the sample. The second type is a result of the presence of the DC voltage. The two types are located at the same place on the electrode, and can, therefore, not be distinguished.
4.2 Experimental method

In the case of a voltage-off test, the electrode charges consist of one type only: the induced charges. The induced charge is normally much smaller than the charge caused by the DC voltage. With the DC voltage on, the observation of the internal space charge profile is more difficult, because charges on electrodes $E_1$ and $E_2$ caused by the DC voltage are present at that moment. In particular, if a homocharge occurs near one of the electrodes, the electrode charge and the homocharge can hardly be distinguished from each other (see Figure 4.5).

Therefore, the voltage-off measurement is particularly useful to obtain a picture of the internal space charge profile only. The voltage-on measurement is useful to get a complete picture of the charge profile of a sample in service. The electric field $E$ in service can then be calculated from this profile.

A complete test of a sample consists of a cycle of actions. The test starts with preparing the sample as described in the section Handling. From there on, voltage-on and voltage-off tests are performed in an alternating manner as depicted in Figure 4.6.

During stage A, the growing of the space charge distribution is measured until the profile no longer changes anymore. Tests are performed at moments on an approximately logarithmic scale, as the charge build-up follows an exponential law. At these moments, a voltage-on test is done, and directly after, a voltage-off test. For the voltage-off test, the DC voltage has to be lowered to zero. Directly after the voltage-off test, the DC voltage is restored, avoiding the charge profile to change. The voltage-off test takes approx. 10 sec.
During stage B, the decay of the charge is followed. Again, the test moments are arranged in a logarithmic way, since the decay follows an exponential law. Voltage-off measurements are made only.

After such a cycle, the test results are saved on a computer disk. These data are numerically treated as described in Appendix A. From these data, relevant information is extracted, such as the maximum charge, the type of charge (positive, negative, homo- or heterocharge), time constants of growth and decay, and the field enhancement factor.

**4.3 Results**

The tests were performed on paper sheet samples, and not on a full-sized cable as mentioned in §4.2.1. This means that the observations and conclusions are applicable to paper sheet samples, and with some restraints (see §4.3.5, the discussion about successive paper-layers), to a full-sized cable.

From all the measurements performed, it can be concluded that there are at least three clear and reproducible behaviours in respect to impregnated paper. These are discussed below. The effects of parameters such as voltage, material characteristics, etc. are discussed in §4.3.1 - §4.3.4. In §4.3.5, tests on combinations of paper and oil layers are discussed.

**Homocharge**

It has been found that, for a broad range of electrical field strengths (20 - 80 kV/mm), and for all types of paper and oil combinations, and for four electrode materials, homocharge is generated. There were no results that differed from this pattern. Homocharges varying from 10 to 60 C/m² were measured. This reproducibility of charge behaviour, irrespective of the various parameters, is quite remarkable, as space charge distributions in plastic samples or PE cables are usually badly reproducible: sometimes they produce homocharge, sometimes heterocharge [55, 41, 65, 64, 98, 63, 28, 19], depending on the chemical content, the material structure, the material treatment, and even on the supplier of the material.

Homocharges in paper are formed both near the anode and the cathode. This means that negative charge injection takes place at the cathode, and positive charge injection at the anode. In general, negative injected charge carriers are thought to be electrons, and holes are mentioned as positive carriers [98, 63,
4.3 Results

90, 33]. In fact, these are no more than assumptions, as the type of carrier cannot be deduced from observations of charge measurement. In dielectrics containing ions, like paper [45, 37], very complex electrode-dielectric interface processes take place, involving electrons, holes and ions.

The injection of carriers in the case of impregnated paper may be explained in two ways. The first explanation assumes that the carriers are injected by the electrodes (see Figure 4.7). If the electrode is a metal, the injected carriers are electrons from the cathode and holes from the anode.

A second possible explanation is that of a process of injection by an oil layer. Paper has a rough surface, if a paper is brought into contact with an electrode, a thin layer of oil (several μm's, the thickness is determined by the surface roughness) will be present between the electrode and the fibre surface. The oil has a different conductivity and permittivity than the impregnated paper, therefore, according to the theory of the Maxwell capacitor [55, 49], a layer of surface charge will be present at the oil-paper interface. As the conductivity of oil is higher than that of the impregnated paper, the surface charge will be of the same polarity as the electrode: homocharge is formed. This layer may act as a charge source. The charge may penetrate further into the paper until balance is obtained. Following this latter theory, the formation of space charge would be independent of the electrode material.

In practice, both processes may take place at the same time, and one of them may be dominant, but it is hard to tell which one. One of the reasons for this is that it is difficult to measure in the region close to the electrode, because of the limited spatial resolution (10 μm in this case).
Figure 4.8 The effect of the broadening of the electrode charge. The space charge adjacent to the electrode is partly overlapped by the measured electrode charge.

In Figure 4.8, an example is given. The left part of the figure shows an exact space charge distribution in a voltage-off case: a negative space charge together with the positive induced charge on the electrode. The electrode charge is very thin, much thinner than the spatial resolution of the system. Due to the limited resolution, the electrode charge appears broader and partly overlaps the space charge adjacent to the electrode.

The right-hand part of Figure 4.8 shows the total measured charge signal. Little can be said about the space charge in the region of the overlap.

From here on, $\rho_{E11}$ will be used to denote the crest of the homocharge adjacent to electrode $Ei_j$ as illustrated in Figure 4.8. A similar definition is used for $\rho_{E12}$. When the electrode material is aluminium, the homocharge will be denoted by $\rho_{Al}$, for other materials, similar symbolic expressions will be used.
The high acoustical attenuation of the paper has already been mentioned in §4.2.1. This attenuation can be modeled by an exponential law

\[
\frac{P_2}{P_1} = \exp[-\alpha (x_2-x_1)],
\]  

(4.1)

where \(\alpha\) denotes the attenuation parameter, \(x_i\) are locations in the sample, and \(P_i\) are the received corresponding pressure peaks. The attenuation parameter was determined by measuring two situations: a paper sample between two aluminium electrodes at an average field strength of +20 kV/mm, and one at -20 kV/mm. This results in two stable homocharge profiles as shown in Figure 4.9.

Homocharge A is formed next to a positive electrode, in the same way as homocharge D. Charges B and C hold a similar relation. There is no difference in the process, as the electrode material, the sample material, and the electrode polarity are the same. Therefore, the difference in peak height is due to the attenuation of the paper only, and can be calculated using equation (4.1), where \(P_2/P_1=D/A\) and \(P_2/P_1=B/C\). For the papers in use, the parameter \(\alpha\) appears to be between 2000 - 5000 m\(^{-1}\). If the two homocharges lie, for instance, 80 \(\mu\)m apart, the second peak will be 0.7 - 0.9 times weaker than the first.

From here the published diagrams will be corrected for this attenuation without further remark.

It is important to realize that the attenuation is compensated for as if it were a frequency-independent phenomenon. In fact, this is not true. The higher frequencies are attenuated more than the lower frequencies. This results in a broadening of the pressure wave. Computing a frequency-dependent correction factor requires signals with a very low noise content and a high resolution. The mathematical technique has been described by Li [66] and Rengel [87]. It has, however, not been used in this thesis.
The homocharge that has been formed on both sides of the paper results in a field enhancement in the middle of the paper and a field decrease at the electrode interfaces.

A field enhancement factor $f$ is calculated by

$$f = \frac{E^{MAX} - E_{DC}}{E_{DC}} \cdot 100\%,$$

where

$$E^{MAX} = \text{MAXIMUM}[E(x)],$$

and

$$E_{DC} = \frac{U_{DC}}{d},$$

and $E(x)$ is calculated with\(^\text{10}\)

$$E(x) = \frac{1}{\varepsilon_0 \varepsilon_r} \left[ \sigma_{E_1} \delta(x=0) + \int_0^x \rho(x) dx + \sigma_{E_2} \delta(x-d) \right].$$

in which $U_{DC}$ denotes the constant DC voltage, $d$ stands for the thickness of the sample, $\sigma_{E_1}$ and $\sigma_{E_2}$ are the electrode charges and $\delta(x=x)$ denotes the impulse function which equals 1 at $x=x$ (see also Figure 4.10).

The field enhancement factor $f$ represents the percentage with which the maximum field strength is increased by the space charge.

\(^\text{10}\) It is assumed that the electric field is a Poisson field in which the permittivity $\varepsilon$ is constant. Furthermore, edge effects are neglected as the width of the high-voltage electrode is much larger than the height of the sample.
In principle, the field enhancement factor $f$ is defined at any time during a test ($f=f(t)$). In this thesis, the factor is used only for the case where a stable situation has been reached,

$$f = \lim_{t \to \infty} (f(t)).$$  \hspace{1cm} (4.6)

Field enhancements from 5 to 100% have been found. More details can be found in the following sections.

When the field enhancements $f$ resulting from different tests are compared with the peak space charges $\rho_{EL}$, it is found that they are almost uncorrelated (see Figure 4.11). The points in the figure are the results of tests made, using all types of paper and oil (see Table 4.2 and 4.3). The slightly ascending slope falls away against the scatter.

![Graph showing the relation between field enhancements $f$ and peak homocharges $\rho_{EL}$ of tests on all paper and oil types. $U_{DC} = 2$ kV.](image)

An explanation is that higher field enhancements result from broad homocharge distributions. Similarly, lower field enhancements result from narrow homocharge distributions (see Figure 4.12). A broader distribution with the same peak value means more total charge. More total charge means in this case a higher field enhancement.

**Figure 4.12** The difference between narrow and broad homocharge distributions.
This has been checked by integrating the charge densities of the measurements over their location in the dielectric and by comparing these with the field enhancement factor $f$ (see Figure 4.13). The integrated value is named $Q$. Indeed, the integrated charge $Q$ clearly increases with increasing field enhancement factor $f$.

**Figure 4.13** The relation between the integrated homocharges $Q$ and the field enhancement factor $f$. The integration has been performed on the charge distributions of voltage-on and voltage-off tests. So, the integration of the results of the voltage-on tests include the electrode charges. $U_{DC} = 2$ kV.

**Difference in charge accumulation and charge decay**

In all these tests, it was found that homocharges appear adjacent to the electrodes and move further into the sample with time (see Figure 4.14). In the middle of the paper the two homocharges meet.
4.3 Results

\[ U = U \]

\[ U = 0 \]

\[ \rho \]

\[ E \]

GROWTH

DECAY

: direction of charge movement

Figure 4.14 Charge profiles start growing from the electrodes (left figure) and decay while staying in the middle of the paper (right figure).

When the external voltage \( U_{DC} \) is lowered to zero, the charge decays, but not in a reverse way as the charge distribution grew. Now, they seem to disappear remaining at their place.

This behaviour may be explained as follows. The charges are injected (either by the electrode dielectric interface, or by the oil layer, as explained). At this moment, the charges are present near the electrode only. Next, they move into the sample until both charges meet. The moving of the charges is governed by the direction of the electric field (see Figure 4.14). When the two types of charges meet, they may recombine. It may happen that the positive and negative charges overlap each other (dotted line in the figure). As only the net space charge can be measured, these two charges cannot be observed separately. Charges might even cross the complete sample and arrive at the opposite electrode. Here they may take part in some complicated ionic interaction process and be adsorbed. The stable charge distribution that will be measured after some elapse of time is a result of the balance between these three processes: injection, recombination and adsorption.

When the external voltage is lowered to zero, the field direction is as illustrated in Figure 4.14 (right-hand side). The charges in the middle of the paper still move toward each other until total recombination has taken place. This makes
the observation of the charges diminishing while remaining in their place understandable.
The charges next to the electrodes will move back towards them and may be adsorbed by the electrodes.

**Time constants**
It was observed that, during every measurement, the growth of the homocharge can be roughly described with two time constants. The first time constant $\tau_1$, which describes a quick growth of charge, is in the order of one minute (0.2 up to 2.5 minutes).
The second time constant $\tau_2$, describes a slow follow-up of the charge growth and is in the order of half an hour to several hours (see Figure 4.15). The scatter in the second time constant, $\tau_2$, is quite large.

When the voltage is lowered to zero, two time constants are observed too. The charge decay occurs fast in the beginning ($\tau_3$ with an order of magnitude equal to $\tau_1$). After a short time, a larger time constant, $\tau_4$, takes over (this time constant is about 10 to 20 minutes).

The existence of two different time constants may be explained as follows. Processes of charge injection are often field dependent\(^\text{11}\). The electrode field is

\[ j = A T^2 \exp \left( -\frac{H_S}{kT} + \frac{1}{2} \beta_S \sqrt{E_{EI}} \right) \]

where $A$, $H$, and $\beta$ are constants of the Schottky process [55, 27]. It is concluded that the

\[^{11}\text{The field-dependent injection holds for injection from the electrode, but also in the case where injection originates from the oil layer, as explained earlier. In the case of electrode injection, an often used physical model is that of Schottky injection. The injection current is given by}

\[ j = A T^2 \exp \left( -\frac{H_S}{kT} + \frac{1}{2} \beta_S \sqrt{E_{EI}} \right) \]
highest immediately after switching on the voltage. A high injection takes place and results in a quick growth of homocharge. The charge lowers the electrode field and, therefore, the charge injection too. Immediately after injection, the charge is transported deeper into the sample and prevents the homocharge peak from saturating immediately. Only when all the processes are in balance (injection, transport, recombination and adsorption), does the peak homocharge become stable. In the light of this explanation, the first time constant, \( \tau_1 \), is more related to the injection process, and the second time constant, \( \tau_2 \), more to the transport and recombination processes.

4.3.1 Effect of voltage

The effect of the external voltage \( U_{DC} \) on the homocharges \( \rho_{Al} \) and \( \rho_{carbon} \) is shown in Figure 4.16. The measurements were performed using samples of paper type I and oil type II. Electrode \( El_2 \) was an aluminium electrode, electrode \( El_1 \) a carbon paper electrode.

For the higher voltages, higher values of homocharges were found. This may be explained by bearing in mind that charge injection in general depends on the field strength at the electrode dielectric interface.

The effect of the external voltage on the field enhancement factor \( f \) is shown in Figure 4.17. The same data were used as those of Figure 4.16.

---

Injection current depends on \( \exp(\sqrt{E_{al}}) \), which means the higher the electrode field strength is, the higher is the injection current.

In the case where injection takes place due to the oil layer, the charge layer that acts as the injection source depends linearly on the external voltage \( U_{DC} \) [55, 49]. The higher this voltage is, the higher is the charge layer.
The field enhancement is more or less independent of the external voltage $U_{DC}$. This was expected: the absolute maximum field $E_{MAX}$ increases with the voltage, due to the higher homocharges, but as the field enhancement factor $f$ is normalized on the average field strength $E_{DC}$, (see equation 4.2) it is more or less independent of $U_{DC}$.

For the higher voltages $U_{DC}$, most of the homocharge grows during the process of the first time constant. In the time described by the second time constant, only little extra charge grows. This effect is shown in Figure 4.18. Within one test, homocharge peaks were measured after a time $t = \tau_1$ and after $t = \tau_2$. This was done for different voltages $U_{DC}$. In the figure, the value $\rho(t=\tau_1)/\rho(t=\tau_2)$ is shown as a function of the voltage $U_{DC}$. The higher $U_{DC}$ is, the more charge has grown within the time described by the first time constant $\tau_1$.

4.3.2 Effect of voltage polarity

The injection processes may depend on the electrode polarity. To examine this, measurements were performed on different polarities. Paper type III and oil type II were used.

It has been found that for both positive and negative polarities, homocharges are formed at both electrodes. In Figure 4.19, the height of the homocharge peaks
at electrode $E_l$ is given as a function of voltage polarity. The height of the homocharge peak $\rho_{Al}$ is slightly lower if the aluminium electrode acts as a cathode than if it acts as an anode. The field enhancement factor $f$, however, stays roughly the same for both polarities (see Figure 4.20).

At both polarities, the occurrence of two time constants $\tau_1$, $\tau_2$, is of the specific growth/decay patterns were observed.

It is concluded that there is no great difference in charge behaviour for different polarities. This means that the charge processes in impregnated paper are, to a great extent, independent of voltage polarity. The conduction process, as well as the recombination process, is most likely to be independent of electrode polarity. It was expected, however, that the electrode processes, like injection and adsorption, depend on polarity. It is striking that in the case of impregnated paper, this assumption is not valid. This observation favours the assumption of an injection process by the oil layer, as described in §4.3.1. According to the observations, this process may be dominant in the electrode injection process.

4.3.3 Effect of electrode material

It is expected that different electrode materials will result in different charge injection behaviour, either in mechanism or in magnitude [28, 1, 55]. Ditchi [28] mentions an increase in homocharge of a factor four to ten when adding zinc stearate to a semiconducting electrode as used in plastic cables. Changing the carbon content in the semiconducting layer resulted in a complete change of the charge pattern [55, 20].
In the present study aluminum, iron, copper and carbon black paper (see Table 4.2) were used as electrode materials. Semiconducting carbon paper is a much used cable paper that is wrapped around the conductor to screen the individual wires and possible sharp edges of the conductor. The comparison is made by collecting the results of tests on paper type II and oil type II. The tests were performed at an average stress of 20 kV/mm. With all types of electrodes, without exception, homocharge is formed. The observation of the two time constants as well as the specific growth/decay pattern also stays valid.

Further, it can be seen that the range of the field enhancement factor \( f \) is the same for all materials (see Figure 4.21). Due to the few number of measurement results per electrode material no quantitative comparison can be made.

However, it seems that the type of electrode material has a minor influence on the charge phenomena in impregnated paper.

![Figure 4.21](image)

**Figure 4.21** The field enhancement factors \( f \) of tests using aluminum, iron, copper and carbon paper electrodes are compared. Paper type II and oil type II were used. The measurements were performed at an average field strength of 20 kV/mm.

4.3.4 Effect of material characteristics

The characteristics of the paper and the oil were shown in Tables 4.2 and 4.3. The characteristics that are discussed here are air impermeability, thickness, kinematic viscosity and electric resistance. A possible relation between these characteristics and the field enhancement \( f \), the peak homocharge \( \rho_{EI} \), and the time constant and \( \tau_2 \) are discussed.

As follows from Tables 4.2 and 4.3, three types of oil were used and four types of paper. Now to consider a possible trend in \( f \), \( \rho_{EI} \) and \( \tau_2 \) as a function of the four characteristics mentioned above, it would be best to have samples of independently varying characteristics. For instance, to consider the impact of paper thickness, at least three types of paper should be used, differing in thickness, but constant in air impermeability. Similar demands apply for the
4.3 Results

other characteristics. In total, this would mean that we should have three types of paper differing only in thickness, three types differing only in air impermeability, three types of oil differing only in kinematic viscosity and three differing only in electrical resistance. From Tables 4.2 and 4.3, it follows that this ideal situation does not apply. The characteristics of the papers are interrelated, and the characteristics of the oil also depend on each other.

Other, more microscopic characteristics like molecule size, fibre length, etc. might be important as well. As those microscopic characteristics cannot easily be changed by the supplier, the pragmatic choice has been made only to observe the impact of the mentioned macroscopic characteristics.

Paper

No clear relation between the peak homocharges $\rho_{EI}$ and the time constant $\tau_j$ with the different paper types has been found. There has, however, a relation been found between the field enhancement $f$, the time constant $\tau_2$ and the paper properties.

In Figure 4.22, $f$ and $\tau_2$ are given as a function of the paper types. The measurements were performed at an average stress of 20 kV/mm. The oil used was type II. It can clearly be seen that paper type III suffers from the highest field enhancement. Paper type I has the lowest field enhancement. The relation between the field enhancement $f$ and the time constant $\tau_2$ is clear.

![Figure 4.22](image1)

**Figure 4.22** The field enhancement $f$ and the time constant $\tau_2$ are related to the paper type.

The relation between $f$, $\tau_2$ and the thickness of the paper (Figure 4.23) and between $f$, $\tau_2$ and the air impermeability of the paper (Figure 4.24) are now considered.

![Figure 4.23](image2)

**Figure 4.23** The field enhancement factor $f$ and the time constant $\tau_2$ are related to the thickness $d$ of the paper.
From these figures, it can be seen that the higher the air impermeability $G$ is, the lower is the field enhancement $f$. Also, the thinner the paper $d$ is, the lower is the field enhancement $f$. Again, it can be seen that $f$ and $\tau_2$ are closely related. As we have seen from Table 4.2, the properties thickness and air impermeability of the samples are not independent. There are two ways to look at this.

First, one may look at a combined quantity $\{d, G\}$ in which the characteristics thickness and air impermeability cannot be distinguished. This would mean that thin and air-impermeable papers have the lowest field enhancements. Paper type I exactly fulfills this demand.

Second, one can build a graph with those paper types that differ only in one characteristic, e.g., thickness $d$ or air impermeability $G$. From Table 4.2, it follows that paper types I and II may be compared when evaluating the air impermeability. Paper types II and IV may be compared when evaluating the thickness. The results are shown in Figures 4.25 and 4.26:

Figure 4.25 The field enhancement and the second time constant related to the thickness of the paper. Only paper types with an equal air impermeability have been used (types II and IV).

Figure 4.26 The field enhancement and the second time constant related to the air impermeability of the paper. Only paper types with an equal thickness have been used (types I and II).

Figure 4.26 shows an descending slope, whereas Figure 4.25 shows a very slight tendency only. It seems, therefore, that the air impermeability of the
paper is the decisive characteristic and not the thickness. However, an insufficient number of measurement points is available to draw a firm conclusion.

Space charge measurement can be useful in selecting the type of insulating paper that suffers the least from field enhancements or, in general, from distortions by space charge.

**Oil**

As with the measurement results of paper, no clear relation has been found between the peak of the homocharge $\rho_{EI}$, the time constant $\tau_1$ and the oil characteristics. But again, a certain relation has been found between the field enhancement factor $f$, the time constant $\tau_2$ and the oil characteristics. In Figure 4.27, the relation between the oil types and $f$ and $\tau_2$ are shown. The oil paper combinations were made with paper type I. An average stress of 20 kV/mm was used. Oil type I suffers from a high field enhancement, while oil types II and III have lower field enhancements.

The oil properties, kinematic viscosity $\eta$ and the electrical resistance $\rho$ are now considered (see Figures 4.28 and 4.29).

**Figure 4.27** The field enhancement factor $f$ and the time constant $\tau_2$ are related to the oil type.

**Figure 4.28** The field enhancement factor $f$ and the second time constant $\tau_2$ are related to the electrical resistance of the oil.

**Figure 4.29** The field enhancement factor $f$ and the time constant $\tau_2$ are related to the kinematic viscosity of the oil.
From the figures, it can be seen that the higher the conductivity \( r \) of the oil is, the higher is the field enhancement factor \( f \). The viscosity shows a similar behaviour: when the kinematic viscosity rises, the field enhancement is first lowered, but for still higher viscosities it rises again.

Space charge measurement can be useful in selecting the type of insulating oil that suffers the least from field enhancements or, in general, from distortions by space charge.

4.3.5 Layers of paper and oil

During production of a full-sized cable, impregnated paper is wound in strips onto the conductor. The paper strips have a certain width, typically 20 mm. During production, a small space is deliberately left between the strips. This facilitates the bending of the cable. These spaces in cable insulation are generally called the butt-gaps (see Figure 4.30). The height of the butt-gaps is determined by the thickness of the paper, the width is determined by the paper insulation machine. The butt-gaps are normally filled with oil. During the cooling phase of the cable in service, several butt-gaps may become filled with gas.

Thin layers of oil (1 to 10 \( \mu m \) thick) are present between successive layers.

An electrical interface is formed between the oil and the impregnated paper. These materials have different conductivities and permittivities, so that, according to the theory of the Maxwell capacitor, a surface charge will be formed [55, 49].
4.3 Results

Butt-gap

In Figure 4.31, such a two-layer system of oil and impregnated paper simulating a butt-gap is shown. Assuming that there is no further space charge present, the layer of surface charge \( \kappa_s \) has a magnitude that depends on the thicknesses \( d \), the conductivities \( \sigma \), and the permittivities \( \epsilon \) of the two layers, and is given by [55, 49]:

\[
\kappa_s = \frac{\sigma_p \epsilon_f - \sigma_f \epsilon_p}{d_p \sigma_f + d_f \sigma_p} U, \quad (4.7)
\]

in which \( U \) denotes the voltage across the system and the subscripts \( p \) and \( f \) stand for impregnated paper and oil (fluid), respectively. The relation between surface charge and measured space charge is given by [55, 49]:

\[
\rho = \frac{\kappa_s}{\nu \Delta T}, \quad (4.8)
\]

where \( \nu \) is the speed of sound in paper and \( \Delta T \) stands for the width of the high voltage pulse.

The time constant of the process of surface charge build-up is given by

\[
\tau_s = \frac{d_p \epsilon_f + d_f \epsilon_p}{d_p \sigma_f + d_f \sigma_p}, \quad (4.9)
\]

As this two-layered setup can be calculated, it serves as a check of the electro-acoustic measurement principle. Measurements using a paper (type I) and oil (type I) combination were performed. A set of one layer of paper and three layers with a circular hole (diameter 20 mm) were subjected to a voltage of \( U = 8 \) kV (see Figure 4.32).
With this setup, the surface charge \( \kappa_s \) and the time constant \( \tau_s \) were calculated. The values of the various parameters were: \( d_p = 100 \mu\text{m} \), \( d_f = 300 \mu\text{m} \), \( \varepsilon_p = 3.5 \), \( \varepsilon_f = 2.3 \), \( \sigma_p = 1.4 \times 10^{15} \Omega^{-1}\text{m}^{-1} \) and \( \sigma_f = 2.9 \times 10^{15} \Omega^{-1}\text{m}^{-1} \). The results of the tests and of the calculation are compared in Table 4.4.

![Figure 4.32 Setup of the paper/butt-gap combination. Paper type I and oil type I have been used.](image)

<table>
<thead>
<tr>
<th>Test number</th>
<th>Measured values</th>
<th>Calculated values</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( \kappa_s [\text{C/m}^2] )</td>
<td>( \tau [\text{min}] )</td>
</tr>
<tr>
<td>1 (t=400 min)</td>
<td>-4x10^{-4}</td>
<td>-</td>
</tr>
<tr>
<td>2 (t=400 min)</td>
<td>-9x10^{-4}</td>
<td>-</td>
</tr>
<tr>
<td>3 (t=1700 min)</td>
<td>-9x10^{-4}</td>
<td>300</td>
</tr>
</tbody>
</table>

Table 4.4

The duration of tests one and two were too short to determine the time constant \( \tau_s \). Also, the surface charges \( \kappa_s \) of tests one and two were not yet at their maximum level. The test and calculation results agree well. It then follows that the electro-acoustic system used here is reliable.

**Successive paper layers**

Tests were made on a one-, two-, three and four layer setup using paper type III and oil type II. A voltage of 3 kV was used across the one layer setup, 6 kV for the two layer setup, 9 kV for the three layer setup and 12 kV has been used for the four layer setup.
Figure 4.33 A comparison of a one, two, three and four layer setup. The large rectangles represent the location of the oil layers. The small rectangles represent the expected surface charges according to Maxwell. The question mark in the four layer setup picture means that nothing can be said of the space charge in the last layer due to the high acoustic attenuation.

In this way an equal average field strength $E_{DC}$ of 20 kV/mm was obtained in both cases. Oil layers of 1-10 μm are assumed between the papers. According to the theory of the Maxwell capacitor as explained before, surface charges are expected on either side of the oil layer(s). The magnitudes are determined by equation (4.7) assuming a homogeneous DC field and appear to be $+4 \times 10^{-4}$ C/m$^2$ and $-4 \times 10^{-4}$ C/m$^2$. The surface charges should be located on either side of the thin oil layer(s) with an assumed distance of 1 to 10 μm.

The results of the one, two, three and four layer setups are shown in Figure 4.33. Four statements follow from the figure.

1) In the one layer setup the homocharges of each polarity fill at least half of the paper (at least, because the figures only show the net charges - positive and negative added. Individual positive and negative charges may overlap each
other. See also the dotted lines in the right hand side of Figure 4.14).
(2) In the two layer setup the homocharges of each polarity fill at least one complete paper layer.
(3) In the three layer setup the homocharges of each polarity fill no more than one paper layer.
It is therefore concluded that the homocharges do not penetrate successive layers, but presumably one layer only.
(4) In the four layer setup, charges are seen at both sides of the interface of the second and third paper layer. These charges are most probably the surface charges as predicted by the theory of the Maxwell capacitor.

If yet more paper layers would be put one after each other, the following layers will probably be free from the homocharge. The layers will have surface charges on both sides of the oil layer as predicted by the Maxwell equations. The effect of the surface charges at that location is the usual higher electric field in the paper than in the oil. In the static situation this difference is determined by the conductivities of the paper and the oil, according to

$$\frac{E_f}{E_p} = \frac{\sigma_p}{\sigma_f}$$  \hspace{1cm} (4.10)

which follows from the current continuity equation $\nabla \cdot J = 0$.

A possible explanation of the charge blocking effect at a paper border could be that the injected space charge recombines with the surface charge that is present at the first paper border. Two necessary conditions are:

- The surface charge must be of an opposite sign as the injected space charge. This is always the case if the oil is more conductive than the paper, which is the case.
- The space charge $\rho(x)$ integrated over its place of occurrence must be in the same order of magnitude as the surface charge $\kappa_s$ (see Figure 4.34).

The magnitude of the calculated surface charge was

![Figure 4.34](image-url)
found to be $4 \times 10^4 \, \text{C/m}^2$. The homocharge integrated over the thickness of the paper (150 $\mu$m) amounted approx. $10 \times 10^4 \, \text{C/m}^2$. The surface charge and the integrated homocharge are therefore of the same order of magnitude and the second condition is fulfilled as well.

Summarized, the necessary condition for charge blocking is that there exists a sufficiently high contrast in conductivity between the impregnated paper and the oil layer, and that the oil is more conductive than the impregnated paper, which in fact is the case in actual cables.

It is concluded that in a multi-layered paper dielectric, homocharge accumulates in layers adjacent to the electrode. The effect on a cable dielectric is as follows.

Under service conditions, the electric field in the paper layers adjacent to the conductor and lead-sheath is lowered, while the field in the layers in the middle of the dielectric is slightly enhanced.

However, after a polarity reversal or during an impulse superimposed on a DC voltage, the field in the paper layers adjacent to the conductor is considerably increased.

### 4.4 Conclusions

Concerning the measurement and behaviour of space charge inside mass-impregnated paper, the following conclusions are drawn:

1. The Pulsed-Electro Acoustic measurement system is a method well-suited for measuring space charge profiles inside mass-impregnated paper.

2. The measurement principle was checked and found valid by measuring the surface charge originating from a paper and oil interface.

3. Regardless of the type of HV paper and HV oil used, and regardless of the electrode polarity and the electrode material used (aluminium, copper, iron or carbon paper), homocharge was formed.

---

$^{12}$ The calculations have been performed for an oil layer of thickness 1 $\mu$m and of 10 $\mu$m. The differences in the results are negligible.
4. Space charge measurements on impregnated paper are reproducible, which is not always the case in the case of polymer samples.

5. In the process of the growing and decaying of the homocharges, two time constants were found. First, a small time constant occurred, in the order of 1 minute. Second, a large time constant was found, in the order of half an hour to several hours.

6. The growth of the charge profile followed a different pattern from that of the decay of the charge. Directly after a DC voltage was put across the sample, homocharge was observed adjacent to both electrodes; not yet in the middle of the paper. After some time, however, the charges reached the middle of the paper.

When then the voltage is removed the charge profile did not change in shape, but in magnitude: the charge profile diminishes while remaining in place.

The explanation is as follows. While growing in the presence of a DC field, charges are injected from the electrodes and only after some time do they arrive in the middle of the paper.

While decaying (when the DC field is removed) the charges in the middle of the paper move further towards each other, due to the resulting local field direction. These charges remain in the middle of the paper and gradually disappear due to a process of recombination.

7. The result of the homocharge formed is a field enhancement in the middle of the paper. In combination with a low resistive oil, thin and high impermeable papers show lower field enhancements $f(4-20\%)$ than to thicker, less impermeable papers (75 - 100%). These observations are well in accordance with the choice of materials in actual HVDC cables.

8. The combination of a thin, highly impermeable paper with high resistive oils leads to higher field enhancements $f (75-90\%)$ than those combinations with less resistive oils (5-30%). These observations are well in accordance with the choice of materials in actual HVDC cables.

9. When combining two or three paper layers, it was found that the homocharges injected by the electrodes do not penetrate much further than one paper layer.

The effect on a cable dielectric is as follows.
Under service conditions, the electric field in the paper layers adjacent to the conductor and lead-sheath is lowered, while the field in the layers
4.4 Conclusions

in the middle of the dielectric is slightly enhanced.
However, after a polarity reversal or during an impulse superimposed on
a DC voltage, the field in the paper layers adjacent to the conductor is
considerably increased.

10. Space charge tests can be useful for selecting the type of insulating paper
and oil, or, in general, the type of insulating material. If the performance
of a new insulating material has to be checked, it is cheaper and less
time-consuming to perform space charge tests on the new sample material
than to perform destructive high-voltage tests on several full-sized cables
that are manufactured with that new material.
CHAPTER 4  Space charges in mass-impregnated paper
A physical model for space charge accumulation in mass-impregnated paper

This chapter presents a physical model that predicts most of the observations made in regard to space charge as presented in chapter 4. The description of the model is divided into two parts. First, the electrical conduction and the injection of charges in impregnated paper are described. This part of the model is found in §5.1.

In §5.2, the conduction and injection models are incorporated in a model for space charge accumulation. The model predicts the occurrence of homocharge in paper and the specific charge growth and decay patterns. It also predicts roughly the magnitude of the charge, the magnitude of the field enhancement factor and the magnitude of the time constant.

5.1 Electrical conduction and injection in mass-impregnated paper

In chapter 2, we stated that the electrical conduction of mass-impregnated paper is field and temperature dependent. The steady-state conduction can be described by equation (2.1) which is given here again:

\[ \sigma = \sigma_0 \exp(\alpha T) \exp(\gamma E), \]  

(5.1)

where \( \sigma_0 \) stands for the conduction at zero field and temperature, \( \alpha \) is the temperature dependency coefficient, and \( \gamma \) is the field dependency coefficient. The equation is an empirical one, based on world-wide experience [77, 45, 80, 21, 17, 18, 78, 75, 94]. Although the formula accurately describes the conduction at different temperatures and fields, it does not clarify the mechanism(s) involved.
Several mechanisms are known from literature: the Poole-Frenkel mechanism [27], modified Poole-Frenkel mechanism(s) [50] and the ionic conduction mechanism [27, 45]. This enumeration gives the most common mechanisms, but is not complete.

For reasons explained below, ionic conduction is the most probable mechanism present in mass-impregnated paper.

In Chapter 4, it was concluded that charge injection takes place in impregnated paper. So far, it has not been decided what charge injection mechanism takes place in paper. Two main injection mechanisms are known from literature: the Schottky injection and Fowler-Nordheim injection [27, 55].

For reasons explained below, Schottky injection is the most probable mechanism at an electrode interface involving mass-impregnated paper.

**Ionic conduction in impregnated paper**

Paper cables are manufactured in a well-conditioned manner. The paper and oil must be of excellent cleanliness. Nevertheless, the insulation may contain impurities [78, 37]. To mention a few: dissolution of the insulation’s own oxidation products, dissolution of metal, dissolution of additives like antioxidant, inhibitor, antistatic agent, pour-point depressant, etc. These impurities and additives may dissociate to form ions. It seems, therefore, logical to suggest that the conduction of paper is of the ionic kind.

The original theory of ionic conduction is based on the movement of ions or vacancies through an ionic crystal [31]. Later, the theory has been used to describe the conduction in polymer materials.

Let us assume a concentration of $N_0$ charged particles with charge $q$ in the insulation. These particles may be trapped in the paper. The trap is represented by a potential energy barrier of height $H$ and width $b$ (see Figure 5.1). The distance between the traps is given by $L$.

![Figure 5.1 A potential energy barrier at zero field.](image-url)
According to the theory, particles hop across the barrier with a certain probability \( p \) per unit time given by [31, 76]

\[
p = \frac{\omega_0}{2\pi} \exp\left[\frac{-H}{kT}\right],
\]

(5.2)

where \( \omega_0 \) stands for the frequency with which the particles hop across the barrier, also known as the attempt-to-escape frequency. The lower the energy barrier \( H \) is, the more probable it becomes that a particle crosses the barrier. A higher temperature results in an enhanced probability of the particle's crossing the barrier.

In the case where no electric field exists, the number of particles that hop from left to right equals the number that hop from right to left. The net particle flux, and therefore the current, is then zero.

Now, when an electric field is applied across the insulation, it results in a shift of the potential energy barrier as shown in Figure 5.2. The barrier height \( H \) is lowered by the value \( \beta E \) for a particle that crosses from left to right. The barrier height \( H \) is increased by the value \( (1 - \beta)E \) for a particle that crosses from right to left.

The probability per unit time for particles that cross the barrier is changed accordingly [31, 76]

\[
p^{r\rightarrow} = \frac{\omega_0}{2\pi} \exp\left[\frac{-H + \beta qBE}{kT}\right]
\]

(5.3)

and

\[
p^{r\leftarrow} = \frac{\omega_0}{2\pi} \exp\left[\frac{-H - (1 - \beta)qBE}{kT}\right]
\]

(5.4)

in which \( p^{r\rightarrow} \) stands for the probability of a particle to hop in the direction of the field (from left to right) and \( p^{r\leftarrow} \) stands for the probability to hop against the
direction of the field. Normally, the shape factor $\beta$ is $\frac{1}{2}$, resulting in a symmetric change of the energy barrier\(^{13}\).

The net particle flux across the barrier differs from zero, due to the perturbing effect of the field on the barrier. The drift velocity $v_d$ in the direction of the field is given by

$$v_d = L(p^+ - p^-). \quad (5.5)$$

Here, it has been assumed that the mean time that particles spend in the path $L$ between two barriers is small compared to the mean time that particles need to cross a barrier. The mobility of the particles is given by

$$\mu = \frac{v_d}{E}. \quad (5.6)$$

The conductivity $\sigma$ follows from

$$\sigma = N_0 q \mu, \quad (5.7)$$

in which $q$ stands for the charge of the particles. Using equations (5.3) to (5.7) and fixing $\beta = \frac{1}{2}$, it finally follows that

$$\sigma = \frac{N_0 q L \omega_0}{\pi E} \exp \left[ \frac{H}{kT} \right] \sinh \left[ \frac{q b E}{2 k T} \right]. \quad (5.8)$$

The potential energy barrier and the process of hopping is a mathematical perception. In reality the process may be described in several ways, three of which will be briefly discussed below.

1. The insulation is full of large polymer molecules: think of the cellulose molecule and the oil molecules. A charged particle (an ion) may be caught by such a polymer molecule. Being caught by such a molecule means that the particle comes into a favourable energy state if it approaches the large molecule, and faces an energy barrier if it tries to escape.

2. Molecules with an electron affinity may be present. When such a molecule comes in the vicinity of a polymer molecule, it may take away an electron of the polymer molecule [50]. The transferred electron can be retained

\(^{13}\) The general case, with $0 < \beta < 1$, is dealt with in [45].
5.1 Electrical conduction and injection in mass-impregnated paper

by the molecule and move as a stable negative ion until it is transferred back
to another polymer molecule.

3. The oil in the insulation is more conductive than the paper [93]. It
follows that the conduction current proceeds mainly in the oil phase along the
pores in the impregnated paper.

According to [37], the pores of the paper fix a large amount of ions of
both signs, with one sign

dominating. This results in a net

charge on the surface of the pores.

Ions of the same sign, which take

part in the conduction process,
suffer from an electrostatic
repulsion force while travelling

through the pores (Figure 5.3). The

repulsion forces can be described by

potential energy barriers. The
distance $L$ between the energy

barriers equals the effective pore

length $l_p$ in this representation.

Process number three is the most probable one.

In order to determine the values of the different parameters in the theoretically
based equation (5.8), this equation is compared with empirical equation (5.1)
of which the parameters are known. We demand that with one set of parameters
of equation (5.8), the relative difference in the results of the two equations was
no more than 100%\(^{14}\) in the whole service range of temperature (0 - 55°C) and
electric field (0 - 30 kV/mm). The values of the parameters were found by
varying them in an iterative way. The values of the parameters for which the
equations match well are given in Table 5.1.

\[^{14}\text{This relative difference is defined as}\]

\[
\frac{\text{theoretical equation} - \text{empirical equation}}{\text{empirical equation}} \times 100\%
\]
Table 5.1 A comparison between the parameters of the empirical equation and the theoretical equation, describing the steady-state conduction in paper.

The match was made for three insulation types. They differ in the values of the temperature and field dependencies $\alpha$ and $\gamma$. Insulation type 1 is the commonly used insulation for mass-impregnated paper cables. Insulation type 2 represents the properties of non-impregnated or gas-filled pre-impregnated paper [78], whereas insulation type 3 is a hypothetic one. The value of the charge $q$ of the carriers was made equal to the charge of one electron $1.6 \times 10^{-19}$ C.

If we have a closer look on Table 5.1, we can conclude that upon changing the temperature dependency coefficient $\alpha$ in the empirical equation, the height $H$ of the energy barrier and the product $N_0 \omega_0 L$ have to be changed in the theoretical equation (compare insulation types 1 and 3). Therefore it may be concluded that the height $H$ of the energy barriers and the product $N_0 \omega_0 L$ (carrier concentration, attempt-to-escape frequency and distance between successive barriers) rule the temperature dependency of the insulation.

In a similar way, it may be seen that upon changing the field dependency coefficient $\gamma$ in the empirical equation, the width $b$ of the energy barrier has to be changed (compare insulation types 1 and 2). Therefore, it is concluded that the width $b$ of the energy barriers rules the field dependency of the insulation.

---

15 In [45] the values of the barrier width $b$ are roughly half the values of $b$ published here. The reason is that in [45] the symmetry factor $\beta$ was set to 0, whereas $\beta$ was set to $\frac{1}{2}$ in this work.
The attempt-to-escape frequency \( \omega_0 \) is fixed at \( 10^{14} \) s\(^{-1} \) \cite{31, 2}, and the distance \( L \) between barriers is fixed at 1 \( \mu \)m\(^{16} \). The concentration of charge carriers \( N_0 \) may be evaluated. The values are given in Table 5.2.

<table>
<thead>
<tr>
<th>Insulation type</th>
<th>( N_0 ) [m(^{-3} )]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.7x10(^{19} )</td>
</tr>
<tr>
<td>2</td>
<td>1.7x10(^{19} )</td>
</tr>
<tr>
<td>3</td>
<td>6.1x10(^{11} )</td>
</tr>
</tbody>
</table>

Table 5.2 Values of the carrier concentration \( N_0 \) as follow from Table 5.2 setting the attempt-to-escape frequency \( \omega_0 = 10^{14} \) s\(^{-1} \) and the distance between barriers \( L = 1 \) \( \mu \)m.

The values of \( N_0 \), \( b \) and \( H \) are within the range that one would expect \cite{55, 59, 50, 97} for an insulator.

In order to show the similarity between the empirical and the theoretical equation, the conductivity \( \sigma \) as a function of temperature \( T \) and electric field \( E \) is shown in Figures 5.4 and 5.5. Insulation type 1 has been used. The largest deviation is found near the low field region (\( E < 10 \) kV/mm).

![Figure 5.4](image1.png) ![Figure 5.5](image2.png)

**Figure 5.4** The conductivity of paper as a function of field strength \( E \) at different temperatures \( T \). The empirical and the theoretical equations are compared.

**Figure 5.5** The conductivity of paper as a function of temperature \( T \) at different field strengths \( E \). The empirical and the theoretical equations are compared.

It is concluded that the theoretical equation describing ionic conduction gives

\(^{16}\) This value will be motivated in §5.2. In fact, in that section, it follows that the model predicts the observations regarding space charges quite well, with values of \( L \) in the order of magnitude of 1 \( \mu \)m.
similar results as the empirical equation which was based on world-wide observations. The similarity in data holds while varying the field and temperature over a wide range: 1-80 kV/mm for the field \( E \) and 0-80°C for the temperature \( T \), which is a wider range than will be met in practice.

It may be concluded that ionic conduction is a probable conduction mechanism in mass-impregnated paper and *that the model proposed here is valid.*

**Schottky injection**
The theory of Schottky injection describes an interface phenomenon. It describes how electrons are transferred from an electrode to an insulator. Initially, the theory was developed for electron injection from a metal into a vacuum. Later on, with a slight modification, the theory was applied to electrode-polymer interfaces as well. Sometimes the theory is used for hole injection too [98, 15, 63, 90, 33].

The Schottky theory is a simplification of what really happens near a metal-polymer interface. In the case of a metal-paper interface, complex electron-ion interactions will be take place, resulting in ions that take part in the conduction mechanism [14]. However, as we are mainly interested in the temperature and field dependencies, we use the Schottky theory just as it is.

The current density at the interface according to Schottky is given by [27]

\[
j = J_0 T^2 \exp \left( -\frac{H_s}{kT} \right) \exp \left( \frac{\beta_s E}{kT} \right),
\]

with

\[
\beta_s = \sqrt{\frac{e^3}{4\pi \varepsilon_0 \varepsilon_r}},
\]

in which \( e \) is the charge of one electron, \( H_s \) is the energy barrier according to Schottky at the electrode-insulator interface and \( J_0 \) is a constant with practical values that may vary within six or seven orders of magnitude [27].
5.1 Electrical conduction and injection in mass-impregnated paper

If we think of the process at the interface as a non-linear conductivity, we may write, using $\sigma = j/E$,

$$\sigma = \frac{J_0 T^2}{E} \exp \left[ -\frac{H_s}{kT} \right] \exp \left[ \frac{\beta N E}{kT} \right].$$ \hspace{1cm} (5.11)

Now it is interesting for which values of $H_s$ and $J_0$ similarity is found with the data of empirical equation (5.1). It was concluded that the similarity could be reached for different combinations of the two parameters. Some of the combinations of $J_0$ and $H_s$ are shown in Table 5.3. Insulation type 1 (see Table 5.1) has been used for this comparison.

<table>
<thead>
<tr>
<th>Empirical</th>
<th>equation (5.1)</th>
<th>Theoretical</th>
<th>equation (5.11)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma_0$</td>
<td>$[\Omega^{-1}m^{-1}]$</td>
<td>$\alpha$</td>
<td>$[^{\circ}C^{-1}]$</td>
</tr>
<tr>
<td>1x10^{-16}</td>
<td>0.1</td>
<td>0.03</td>
<td>30</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1000</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>3x10^4</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1x10^6</td>
</tr>
</tbody>
</table>

Table 5.3 A comparison between the parameters of the empirical and the theoretical equation, describing the charge injection in paper.

There appears to be a relationship between the parameters $H_s$ and $J_0$ describing the combination of parameters leading to similarity in the data. This empirical relationship, proposed here by the author, is given by

$$\ln J_0 = AH_s + B,$$ \hspace{1cm} (5.12)

where $A$ and $B$ are constants with values 34 eV^{-1} and -27.2 \(^17\) respectively. The relation may be used for values of $H_s$ between 0.9 and 1.2 eV and

\(^{17}\) In the ionic conduction model, such a relationship between the barrier height $H$ and the product $N_0\omega L$ has been found too. The relationship is valid for a slightly smaller range of these parameters (0.9 eV < $H$ < 1.1 eV) than is the case with the Schottky injection model. As this extension of the theory would have complicated the reasoning regarding the ionic conduction model too much, it has not been mentioned.
corresponding values of $J_0$. For values outside this interval, the similarity in data is lost. This is not a problem, because the values of the parameters too much outside the interval do not occur in actual conduction cases.

In order to show the similarity between the empirical (5.1) and the theoretical equation (5.11), the conductivity $\sigma$ as a function of temperature $T$ and electric field $E$ is shown in Figures 5.6 and 5.7. In this specific case, a value of 0.9 eV has been used for $H_s$ and 30 Am$^{-2}$K$^{-2}$ for $J_0$, i.e. the first combination in Table 5.3. Other combinations as given in Table 5.3 could have been used as well. Again, the largest deviation is found in the low field region ($E < 10$ kV/mm).

![Figure 5.6](image1.png)  
**Figure 5.6** The interface conductivity of paper as a function of field strength $E$ at different temperatures $T$. The empirical and the theoretical equations are compared.

![Figure 5.7](image2.png)  
**Figure 5.7** The interface conductivity of paper as a function of temperature $T$ at different field strengths $E$. The empirical and the theoretical equations are compared.

The magnitude of the interface conductivity according to Schottky as a function of temperature $T$ and field $E$ gives results similar to the empirical equation (5.1) over a wide range of temperature $T$ and field $E$. The similarity in data holds while varying the field and temperature over a wide range: 1-80 kV/mm for the field $E$ and 0-80°C for the temperature $T$, which is a wider range than will be met in practice.

It is, therefore, concluded that Schottky emission is a probable mechanism that occurs at an electrode insulator interface in which impregnated paper serves as the insulator.

*Other mechanisms*

It has been checked as to whether other conduction and injection mechanisms could have been used to describe the conductivity as observed. The Poole-Frenkel mechanism [27], and a modified version of the Poole-Frenkel mechanism [50], have been compared with the empirical equation (5.1) as
representatives of other conduction mechanisms. The Fowler-Nordheim mechanism [27] has been compared with the empirical equation (5.1) as an alternative to the injection mechanism, although this mechanism is unlikely to happen as it occurs at very high field strengths only.

None of these conduction and injection mechanisms gave satisfactory results. It was concluded that these mechanisms were not likely to dominate in impregnated paper.

5.2 Space charge accumulation in mass-impregnated paper

The ionic conduction model and the Schottky injection model will now be used to build a model that agrees well with the observations of charge accumulation in paper.

The bulk of the paper is represented by successive energy barriers separated by a distance $L$ (as introduced in §5.1, see Figure 5.8). The energy barriers are set up both for positive and negative charge carriers. An initial charge density, given by the parameter $N_0$ (prescribed by the ionic conduction model), is present. It is divided into a concentration $N_0/2$ for the positive carriers and $N_0/2$ for the negative carriers, thus forcing the sample to be electrically neutral.

At the cathode, Schottky injection of negative carriers takes place, while Schottky injection of positive carriers is assumed at the anode.

If carriers reach the opposite electrode, it is assumed that they are immediately adsorbed by that electrode\textsuperscript{18}.

\textsuperscript{18} Charge adsorption by an electrode is not as well understood as charge injection. Different authors [40, 33] describe different behaviours.
It is assumed that carriers of both signs which meet, recombine at a certain rate. The author proposes to model the rate of recombination at location \(i\), \(r_i\), as a fixed percentage \(R \times 100\%\) of the carrier concentrations \(N_i^+\) and \(N_i^-\) at location \(i\) in the paper. Below the initial concentration \(N_0\), no recombination takes place; this is incorporated in the model as an offset \(r_o\) in the recombination function. This is reasonable, as we have seen in \$5.1\) that a carrier concentration of \(N_0\) was necessary for the steady-state conduction. The recombination function is given by\(^{19}\):

\[
\begin{align*}
    r_i &= r_o + R \left( \frac{N_i^+ + N_i^-}{2} \right) \quad \text{if} \quad \left( \frac{N_i^+ + N_i^-}{2} \right) \geq N_0 \\
    r_i &= 0 \quad \text{if} \quad \left( \frac{N_i^+ + N_i^-}{2} \right) < N_0.
\end{align*}
\]

(5.13)

Figure 5.9 shows the function with values \(R = 0.3\%\) and \(r_o = -N_oR = -5.1 \times 10^{10}\) m\(^{-3}\) (in which \(N_0 = 1.7 \times 10^{13}\) m\(^{-3}\)).

Before using the model, the different parameters must be chosen. The parameters of the ionic conduction model and the Schottky injection model were fixed in \$5.1\), when considering the steady-state conduction dependencies on temperature and field. This leaves us with four parameters:

1. The rate of recombination \(R\).
2. The distance between successive energy barriers \(L\).
3/4. The relation between the steady-state carrier concentration \(N_0\), the attempt-to-escape frequency \(\omega_o\) and the distance \(L\) between successive barriers. Only the product \(N_0\omega_oL\) is known (\(1.7 \times 10^{27}\) m\(^{-2}\)s\(^{-1}\)), not the separate values.

\(^{19}\) A slightly different recombination function has been used by [33]. However, the reasoning was the same: the rate of recombination taking place as a fixed percentage of the carrier concentration at a certain location.
5.2 Space charge accumulation in mass-impregnated paper

To fix the values of these parameters, we have to consider what the effect of these parameters is on:
- the appearance of homocharge and not heterocharge,
- the growth and decay patterns,
- the order of magnitude of the charge density $\rho$,
- the order of magnitude of the field enhancement factor $f$,

as observed in Chapter 4.

The predictions of the model are then compared with the observations that were made. The values of the parameters $R$, $L$, $N_0$, and $\omega_0$ which result in predictions that are the closest to the observations will be the final values.

**Figure 5.10** The process of charge growth according to the model. The upper graph shows the electric field $E_{rel}$ relative to a homogeneous DC field as a function of place. The bottom graph shows the charge density $\rho$ as a function of place.

**Figure 5.11** The process of charge decay according to the model. The upper graph shows the electric field $E_{rel}$ relative to a homogeneous DC field as a function of place. The bottom graph shows the charge density $\rho$ as a function of place.
As a general example, the results of a simulation are given with $R$ equal to 0.3%, $L$ equal to 1 $\mu$m, $N_0$ equal to $1.7 \times 10^{19}$ m$^{-3}$ and $\omega_0$ equal to $10^{14}$ s$^{-1}$ (for each parameter the average in the previously mentioned range is used). The conduction and injection properties for both positive and negative charge carriers and electrodes were chosen to be the same. The sample was 100 $\mu$m thick and the external voltage $U_{DC}$ was set to 2 kV.

Figure 5.10 shows the growth of space charge and the change of the electric field starting from time $t=0$ at an initial space charge free sample.

Figure 5.11 shows the decay of the space charge and the change of the electric field. The voltage $U_{DC}$ was 0 kV. The simulation of the decay started from the end of the former simulation of the charge growth.

The model adequately predicts the accumulation of homocharge and the growth-decay patterns as observed during the tests as shown in Chapter 4. During the growth of the charge profile, space charge is injected from the electrodes and moves gradually into the interior of the paper. When the charges of both signs meet in the middle of the paper they recombine. If the voltage is removed, the charge profile stays about the same, but diminishes in the course of time.

The field enhancement factor $f$ reached a value of 45% in this case. Measured values range from roughly 5 to 100%.

The maximum charge $\rho$ adjacent to the electrode in this particular case reached 60 C/m$^3$. Measured values range from roughly 10 to 35 C/m$^3$ (see Chapter 4). As the resolution of the measurement system was limited to some 20 $\mu$m, this value could never have been observed. The maximum charge density, disregarding the regions 0-20 $\mu$m and 80-100 $\mu$m, is 15 C/m$^3$.

All these values are well within the order of magnitude as observed during the tests.

The simulation does, however, not predict the appearance of two time constants during the growth of the charge profile, as observed in Chapter 4. The growth of the space charge according to the model is described with one time constant only, which in this particular case was 42 min. Within the range of the}

\footnote{The observations of the two time constants were made in Chapter 4. The first time constant $\tau_1$ is about <1 min. The second time constant $\tau_2$ varies within a wide range from about 30 to 500 min.}
5.2 Space charge accumulation in mass-impregnated paper

parameters used, the calculated time constant roughly varies between \( \frac{1}{2} \) and 1\( \frac{1}{2} \) hour.

Varying the parameters

Figures 5.10 and 5.11 show the appearance of homopolar and the growth-decay pattern, as a result of computation with one set of parameters. But, the model predicts the accumulation of homopolar and the growth-decay profiles also for a wide range of values of the parameters \( R, L, N_0 \) and \( \omega_0 \); this was concluded after having computed the charge profiles using different values of the parameters. The model is, therefore, quite robust in predicting the different properties.

In the following, the effect of the parameters on the charge density \( \rho \) and the field enhancement factor \( f \) are given.

Varying the rate of recombination \( R \)

The effect of the rate of recombination \( R \) on the field enhancement factor \( f \) and the charge density \( \rho \) is shown in Figure 5.12. Parameter \( L \) has been set to 1 \( \mu \)m, parameter \( N_0 \) to \( 1.7 \times 10^{19} \) m\(^{-3}\) and parameter \( \omega_0 \) to \( 10^{14} \) s\(^{-1}\). The voltage \( U_{DC} \) was 2 kV and the thickness \( d \) of the paper was 100 \( \mu \)m.

From the figure, we see that the higher the rate of recombination is, the higher is the field enhancement \( f \).

The charge density is represented by a line describing the charge density, disregarding the first and last 20 \( \mu \)m of the sample (further named "restricted" charge density). The restricted charge density is quite independent of the field enhancement factor.

The predicted values of charge density \( \rho \) and field enhancement factor \( f \) are well

\[ \text{Figure 5.12 The field enhancement factor } f \text{ and the charge density } \rho \text{ as a function of the rate of recombination } R. \]

\[ \text{The parameters } L, N_0 \text{ and } \omega_0 \text{ have been varied two orders of magnitude. Parameter } R \text{ has been varied even more than two orders of magnitude.} \]
within the range of observed values as found in Chapter 4 (see Figure 4.11), while varying the rate of recombination \( R \) from 0.01\% to 10\%.

**Varying the distance \( L \) between energy barriers**

The effect of the distance \( L \) between successive barriers on the field enhancement factor \( f \) and the charge density \( \rho \) is shown in Figure 5.13. Parameter \( R \) has been set to 0.3\%. The *product* \( N_0 \omega_0 L \) is kept constant and equals the value as found in §5.1 \((1.7 \times 10^{37} \text{ m}^2\text{s}^{-1})\). Therefore, as \( L \) is varied, \( N_0 \omega_0 \) is varied too. The voltage \( U_{DC} \) was 2 kV and the thickness \( d \) of the paper was 100 \( \mu\text{m} \).

The larger the distance \( L \) between the energy barriers is, the lower is the field enhancement factor \( f \). The restricted charge density remains relatively constant.

The magnitude of \( L \) had to be chosen in the order of magnitude of 1 \( \mu\text{m} \) in order to match the predictions of the model with the observations. Observe that the magnitude of \( L \) (0.1 - 10 \( \mu\text{m} \)) is within the range of macroscopic properties like the fibre and the pore lengths \( (l_p) \) within the paper. This supports the theory that ions have to overcome coulombic forces when entering a pore structure (see §5.1 - ionic conduction).

The predicted values of charge density \( \rho \) and field enhancement factor \( f \) are well within the range of observed values as found in Chapter 4 (see Figure 4.11), while varying the distance \( L \) between energy barriers from 0.3 \( \mu\text{m} \) to 5 \( \mu\text{m} \).
5.2 Space charge accumulation in mass-impregnated paper

Varying the carrier concentration $N_0$ and the attempt-to-escape frequency $\omega_0$.

The effect of the relation between carrier concentration $N_0$ and the attempt-to-escape frequency $\omega_0$ on the field enhancement factor $f$ and the charge density $\rho$ is shown in Figure 5.14. The product $N_0\omega_0L$ is kept constant and equals the value as found in §5.1 (1.7×10^{27} \text{ m}^2\text{s}^{-1}). Parameter $R$ has been set to 0.3 % and parameter $L$ has been set to 1.7 $\mu$m. The voltage $U_{DC}$ was 2 kV and the thickness $d$ of the paper was 100 $\mu$m.

The higher the carrier concentration $N_0$ is, the higher is the field enhancement factor $f$. The restricted charge density remains fairly constant.

The predicted values of charge density $\rho$ and field enhancement factor $f$ are well within the range of observed values as found in Chapter 4 (see Figure 4.11), while varying the carrier concentration $N_0$ from $10^{18}$ m$^{-3}$ to $10^{21}$ m$^{-3}$ and the attempt-to-escape frequency $\omega_0$ from $10^{13}$ s$^{-1}$ to $10^{15}$ s$^{-1}$.

Conclusions

It is concluded that the field enhancement factor $f$ and the restricted charge density remain within the values as observed. This is regardless of a wide variation in the parameters $L$, $R$, $N_0$ and $\omega_0$.

The distance $L$ between successive energy barriers is in the order of magnitude of the paper pore lengths $l_p$. This supports the theory that the energy barrier is a result of the repulsion forces between ions near the entrance of a pore.

Upon varying the different parameters, it was seen that it hardly affected the restricted charge density. This may explain why the observed values of maximum charge density in Chapter 4 are quite independent of the paper type.

Finally, it is concluded that this physical model predicts the observations quite well. This gives a firm physical base for the observations that were made in Chapter 4.
CHAPTER 5  Physical model for space charge accumulation...
Proposals for test requirements

Testing of cables, terminations and joints is necessary to ensure the quality of the product. Over the past decades, an adequate set of tests for high voltage AC cables has been developed. As a result the high voltage AC cable systems that are in service now are of a high quality and reliability.

HVDC cables are just as reliable as high voltage AC cables. Their tests, however, are less well developed. A set of electrical test recommendations exists, generally known as the ELECTRA 72 document [22]. For the development of a new generation of HVDC cables, a more advanced set of tests would be desirable.

In §6.1, the philosophy behind the testing HVDC cables is given. The results of this may be found in §6.2 in regard to the type test, in §6.3 in regard to the routine test, in §6.4 in regard to the factory joint test and in §6.5 regarding the factory acceptance test. This chapter ends with conclusions in §6.6.

6.1 Test philosophy

A DC link is made up of different objects, which have to be tested to control their quality. To make the discussions in this chapter clear, the definitions of the different objects and tests is given first.

Objects
There is a common DC link between the following objects: manufacturing lengths, factory joints, delivery lengths, field joints, repair joints and transition joints. These objects together make up the complete circuit, see Figure 6.1.
A manufacturing length is defined as one continuous production length without factory joints (see Figure 6.1). The manufacturing length is a half-product and is not yet armoured. A manufacturing length can be as long as 30 km, depending on the factory.

A factory joint is a joint made in the factory. The joint connects two manufacturing lengths (see Figure 6.1) and has the same overall diameters as the manufacturing length. The joint has a continuous armouring.

A delivery length is defined as the cable that will be shipped in one piece (see Figure 6.1). This length is armoured and may include factory joints. A delivery length may be as long as 100 km, depending on the laying vessel.

A field joint connects two delivery lengths (see Figure 6.1). This joint is not made in the factory, but made on site.

A repair joint is a special type of field joint and is used to repair a cable in which a fault has occurred. The joint is made on site and is generally of the same design as the field joint.

A transition joint connects two cables of different design, for instance, a land cable and a shallow-water cable. Sometimes, different types of cables must be connected, for instance, an oil-filled cable with a mass-impregnated cable.

The circuit is defined as the total of all delivery lengths, including all types of joints and the terminations.

A termination (or sealing end) is the accessory that connects an overhead line, or, in general, the high voltage feeder, with the cable.

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22 The manufacturing lengths are often referred to as factory lengths. To avoid confusion with the factory acceptance test (which is not performed on factory lengths), we use the term manufacturing length only.
6.1 Test philosophy

Tests
A distinction is made here between type tests, routine tests, factory joint tests, factory acceptance tests and after-laying tests.

A type test is made on a representative piece of cable in order to qualify the design and the manufacturing methods of the cable system to meet the intended application. The nature of the type test is such that, after it has been carried out, it need not be repeated unless changes are made in either the material, the design, or the process parameters outside the tolerances which affect the lifetime of the cable.

A routine test is made on every manufacturing length to demonstrate the integrity of that cable and to verify that the product meets the design and manufacturing specifications. Overvoltage tests are made on the full length, but as it is not feasible to perform diagnostic tests on full manufacturing lengths (see Chapter 6) it is proposed by the author to perform the diagnostic tests on a representative length of 30 to 100 metres.

A representative length could be:
- a length cut from the beginning of a manufacturing length,
- a length cut from the end of a manufacturing length,
- and/or a separate length that is manufactured and impregnated in the same batch as the manufacturing length.

A factory joint test is introduced as a routine test, specially dedicated to the factory joints.

A factory acceptance test is a set of tests to be performed on each delivery length. This length may include factory joints. A factory acceptance test is introduced for two reasons. The delivery length, unlike the manufacturing length, will have passed through extra manufacturing steps like jointing, armouring and finishing. To take these extra steps into account, the factory acceptance test is performed.

Another important reason to introduce this test is to show that the cable is in good electrical condition before it leaves the factory and is transferred to another company (for instance the laying company).

An after-laying test is a test to be performed on the complete circuit. It is important to realize that field joints, repair joints, transition joint(s) and terminations are tested only during the after-laying test.
Overvoltages
The cable will suffer from different types of overvoltages: AC overvoltages, lightning and switching impulses and several combined types of overvoltages. The question of which type of overvoltages are to be taken into account in the tests should be examined.

Impulses are a serious threat to at least the first few kilometers of cable next to a convertor station. They must be taken into account in the testing. Impulse tests are required in the type test. There is a lot of information on the methods of impulse testing [42, 43] and the results of impulses on impregnated paper cables [56, 24, 60, 86, 8, 9, 35, 3]. Impulses *superimposed* on a DC voltage are of special importance (see Chapter 2.4).

The risk of AC overvoltages was much reduced with the introduction of modern convertor stations [24]. The occurrence and duration of such convertor faults differ much per case. It is recommended that the incorporation and definition of an AC test be discussed between manufacturer and user.

The same holds [24] for the combined type of overvoltages (AC+DC, damped oscillating waves+DC, etc.). A suitable test should be agreed upon between manufacturer and user.

Ageing
During its lifetime, the cable will suffer from electric and thermal fields. It is to be expected that the cable will age because of these fields. This point needs some special attention, and therefore the AC case is briefly reviewed first.

It has been shown that high voltage AC cables age under electric and thermal stresses. In general, this electric ageing may be described with the "life-line". This relates the measured lifetime $L$ at a voltage $V$ to the expected lifetime at that voltage. This life-line is generally described by an inverse power law

$$L = V^{-a}.$$  \hspace{1cm} (6.1)

The complete lifetime of a cable may thus be consumed in a shorter time at a higher test voltage. This principle is used in the stability test, which is a part of the type test. Generally, the operating temperature affects the lifetime too. Stability tests are performed at an enhanced (conductor) temperature, thus taking into account the thermal ageing of the cable as well.
6.1 Test philosophy

A higher test voltage than the service voltage is also used during routine tests. The test voltage should be chosen such that there is a high probability of eliminating manufacturing defects. However, the test voltage should not be chosen to be too high in order to ensure that the loss of life during the test is below a certain level.

It is clear that the concept of overvoltage testing is accepted and used in the testing of high voltage AC cables.

We now consider the equivalent case of DC voltage testing. The recommendation for testing HVDC cables (ELECTRA 72 [22]) uses the concept of overvoltage testing as well. It is assumed that a life-line exists also for HVDC cables [55]. Let us try to build a life-line on the existing knowledge of HVDC mass-impregnated cables. As a basis for the stability test and a required minimum life of 30 years, a minimum life-line, represented by line a (see Figure 6.2), is assumed. This line is based on a voltage level of twice the service voltage during 30 days, as required by the ELECTRA 72 document when performing a stability test.

A submarine cable which has been in service for over 30 years (and which were tested at that time according to the ELECTRA 72 document) have been investigated. No visual, electrical and chemical deterioration has been found in the cable [39]. A complete type-test programme was again performed on this cable, and the cable passed without any problem [39, 83]. This means that the cable has twice passed an expected lifetime of 30 years: 30 years in service and 30 years at the accelerated test.

Therefore, the life-line of the current generation of cables must be situated at least at line b as represented in Figure 6.2. And as no visual and chemical signs of ageing have been found, the life-line may probably be situated higher, line c, for instance.

The ELECTRA 72 document is currently under revision. The value of testing at 2U₀ is the value recommended by the old version of ELECTRA 72 which is still in use at the moment of writing.
The conclusions so far are threefold.
1. The knowledge concerning the life-line and the ageing of the current
generation of HVDC mass-impregnated cables is incomplete.
2. The chosen overvoltages during testing are not too high, because no
considerable lifetime was consumed.
3. The design parameters of the current generation of cables are safe up till
now and some of them, perhaps, too safe.

Environmental parameters
In general, a stability test must take care of all the critical environmental
parameters that may take part in the ageing process of the cable. The most
important parameters are temperature, water pressure and steep slopes.

Of temperature, we know that it may have a severe impact on the cable. This
is true for the cooling down of a cable (stage III*, see sections 3.3.2 and 3.4),
but also for the ambient temperature during cooling down. A cable lying in a
cold environment (deep-sea, for instance) may suffer more during stage III* than
the same cable lying in a warm environment (land, for instance) or vice versa
[30, 84]. This may depend on the cable design and materials. Therefore,
temperature as an enviromental parameter has to be taken into account during
testing.

It can be argued as to whether external pressure also should be taken into
account. In fact, the high water pressure to which a deep-water cable is exposed
helps the insulation to close voids (for this reason deep-water cables are
sometimes referred to as water-pressure assisted cables). High external pressure
is therefore not a critical parameter, and it is not recommended that it be taken
into account as a general requirement in electrical testing.

A cable route may pass over steep slopes. In such a case, there is a risk of
compound migration, which thus threatens the performance of the cable. It is,
however, difficult to write a general rule prescribing which slopes are
dangerous and which are not. It should be agreed between the manufacturer and
the user whether the impact of a steep slope shall be taken into account during
testing.

Overvoltage tests and diagnostic tests
Most of the tests recommended by the ELECTRA 72 document are based on
the concept of overvoltage testing and heat cycling. As mentioned before, cables
that have been in service for over 30 years, and that were tested at that time in
accordance with these recommendations, did not show any sign of ageing [39].
Therefore, the concept of overvoltage testing and heat cycling is satisfactory for the current generation of HVDC cables \((U \leq 450 \text{ kV}, P \leq 600 \text{ MW})\). But, for new generation HVDC cables with larger transmission capacities, the question arises as to whether diagnostic tests should be added to the existing tests. The goal of an increased transmission capacity of HVDC cables can be reached in at least three ways:

1. Use the same design parameters (maximum field strength, maximum temperature, etc.) and increase the size of the cable.
2. Increase some design parameters (preferably the maximum field strength\(^{24}\)).
3. Use new insulation materials.

In all three cases, there is a need for diagnostic tests.

1. If the dimensions of the cable are significantly increased, a scaling effect may take place. Although the design parameters have not changed, other parameters, which were not considered important, may have changed and now take part in the ageing process. As the life-line is not fully known, the concept of overvoltage testing alone is now not a firm base. A diagnostic test, to sense possible ageing mechanisms during testing, should be added.

2. If a design parameter, for instance the maximum field strength, is increased, it is not known whether the design parameter is safe. Again, a diagnostic test could be added, to monitor a possible ageing mechanism during testing.

3. In the case of new materials, another life-line may be valid and the same reasoning applies. Possible diagnostic tools are: partial discharge measurements, dielectric current measurements and loss angle \((\text{tg } \delta)\) measurements.

In the following sections, a proposal is made for the type tests, routine tests, factory joint tests and factory acceptance tests in regard to HVDC cables of the mass-impregnated type. The proposal is made in accordance with the ELECTRA 72 document and is extended with the experiences as reported in this book.

\(^{24}\) An increase of the maximum design temperature may lead to the risk of compound migration, especially at steep slopes. This in turn leads to dry spots in the insulation, where partial discharges may take place, thus harming the cable. Therefore, the maximum temperature should preferably not be increased.
6.2 Type test

Before entering the stage of type testing, the objects to be tested should be defined. In general, the objects will be: deep-water cable, shallow-water cable\textsuperscript{25}, land cable, termination, factory joint, field joint, repair joint, and possibly a transition joint. Which objects are involved depends on the specific project.

Type test sets
In §6.1, it has been stated that a type test must take care of critical environmental parameters. We have recognized the ambient temperature to be such a parameter. An HVDC cable circuit may experience different ambient temperatures along the route. A land cable may experience a high ambient temperature (for instance 35\textdegree C). An unburied, deep-water cable may experience the minimum sea temperature of 4\textdegree C.

A cold environment or a warm environment may be of critical influence on the performance of HVDC cables [30, 84], depending on the design and the material (see also §2.2.7). Therefore both situations must be tested. This means that two complete type tests at two different ambient temperatures must be performed. This is a costly and time-consuming way of testing. It may be simplified if it is recognized that, in practice, not all objects will experience these temperatures. A matrix can be set up to define which objects experience both warm and cold situations and which experience just one of them. Table 6.1 serves as an example. For reasons of simplicity, no difference has been made between land joints, shallow-water joints and deep-water joints. In practice, more objects may have to be tested.

<table>
<thead>
<tr>
<th></th>
<th>Deep-water cable</th>
<th>Shallow-water cable</th>
<th>Land cable</th>
<th>Factory joint</th>
<th>Field joint</th>
<th>Repair joint</th>
<th>Transition joint</th>
<th>Termination</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cold</td>
<td>X</td>
<td>X</td>
<td></td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Warm</td>
<td></td>
<td>X</td>
<td>X</td>
<td></td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
</tbody>
</table>

Table 6.1 An example matrix defining which objects experience a high and a low ambient temperature.

\textsuperscript{25} A distinction is made between a deep-water and a shallow-water cable because the designs may be different. The cables differ mostly in the mechanical design.
6.2 Type test

From this *example* matrix, the different test sets can be defined. In table 6.2, possible test sets as follow from table 6.1 are shown. As an example, the deep-water cable is tested separately in Set 2. This, introducing even more but smaller test sets, can be advantageous in the case of a breakdown in one of the test sets. In that case, *one* test set has to reenter the type test only.

<table>
<thead>
<tr>
<th>Set 1 Cold</th>
<th>Shallow-water cable</th>
<th>Factory joint</th>
<th>Field joint</th>
<th>Repair joint</th>
<th>laboratory terminations permitted</th>
</tr>
</thead>
<tbody>
<tr>
<td>Set 2 Cold</td>
<td>Deep-water cable</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Set 3 Warm</td>
<td>Shallow-water cable</td>
<td>Land cable</td>
<td>Field joint</td>
<td>Repair joint</td>
<td>Transition joint</td>
</tr>
</tbody>
</table>

Table 6.2 Three possible test sets that all have to be type tested. The termination is tested at a temperature determined by the ambient temperature of the test hall.

Three sets have to be type tested, two of them in a cold situation and one of them in a warm situation. The actual termination is tested only once, as difference in ambient temperature generally does not greatly affect the performance.

The type testing of the same objects twice under different ambient conditions is a new concept which is not known from the testing of AC cables.

Tables 6.1 and 6.2 serve as an example. The exact definition of the type test sets depends on the project, the cable route and the design of the joints. It is therefore recommended that the definition of these sets be left to be determined on the basis of discussion between the manufacturer and the user.

*Test programme for type tests*

A proposal for a new type test programme will now be given. It is based on the ELECTRA 72 document [22]. Tests marked with an asterisk* are new and cannot be found in the ELECTRA 72 document. Details concerning the techniques of performing the tests not marked with an asterisk can be found in the ELECTRA 72 document.

- Mechanical tests. Tests differ for deep-water, shallow-water and land cables.
Stability test (at specific ambient temperature).
- 10 temperature cycles at a positive voltage of 2U₀.
- 10 temperature cycles at a negative voltage of 2U₀.
- 10 temperature cycles with polarity reversals at 1.5U₀.

Partial discharge measurements at appropriate times during the stability test.
Requirement: During the first 4 hours after the cessation of the load: 
\[ nq \leq 0.5 \text{ nC·min}^{-1}. \]

Superimposed lightning impulse test: 10 negative lightning impulses superimposed on a positive voltage of 1U₀, followed by 10 positive lightning impulses superimposed on a negative voltage of 1U₀. The cable must be loaded.

Superimposed switching impulse test: 10 negative switching impulses superimposed on a positive voltage of 1U₀, followed by 10 positive switching impulses superimposed on a negative voltage of 1U₀. The cable must be loaded.

Dielectric current test.
Loss angle test.

Detailed information is given below.

**Polarity reversal**
Regarding the polarity reversals during part of the stability test it should be noted that the electric field is highest immedately after the polarity reversal, after which it may drop quickly (see section 2.2.6. This situation applies especially to the test set which is tested at a high ambient temperature, as then the field at the conductor drops more quickly than in a cold situation). The polarity reversal should therefore be performed within a short period of time: at least less than 10 minutes and preferably within 2 minutes [22].

**Partial discharge test**
The partial discharge test could be performed during the whole stability test. The requirement, \[ nq \leq 0.5 \text{ nC·min}^{-1}, \] applies in principle for the whole stability test. The test is the most appropriate, however, during the first four hours after switching off the load. In this time span, the most harmful...
discharges may take place (see sections 3.3.2 and 3.4).

The accomplishment of the rule is motivated by two reasonings.

1. Kreuger [55] proposed to display the partial discharges in a $q(n)$ graph and demanded that $nq \leq 2 \text{ nC min}^{-1}$.

In Figure 6.3, a $q(n)$ graph is shown and the requirement is drawn in the graph as a solid line, marked with the letter $K$. The line divides the cables into "GOOD" and "BAD". Kreuger proposed this type of requirement on the basis of literature discussing different types of energy and non-energy HVDC equipment. The level of the requirement, $2 \text{ nC min}^{-1}$, could according to him, be changed, based on the observations made on specific equipment (see Figure 6.3).

2. To adjust the level of the requirement to an HVDC cable, the following experiment was carried out. Cables of types A and B were tested several times during stage III at a negative voltage of 350 kV. The maximum conductor temperature of the cables reached before switching off the load was always less than 50°C. The results of the measurements were entered in the $q(n)$ graph.

A type B cable was also tested several times during stage III at a negative voltage of 350 kV. The maximum conductor temperature of this cable was now considerably more than 50°C before

Figure 6.3 The proposed requirement to discriminate between "GOOD" and "BAD" objects.

![Figure 6.3](image-url)

Figure 6.4 The results of discharge measurements during stage III displayed in a magnitude versus repetition rate graph. The proposed "GOOD" and "BAD" regions have been drawn in.

![Figure 6.4](image-url)
switching off the load. This means that the cable was deliberately overloaded. The overloaded cables did not pass a shortened type test according to the ELECTRA 72 document. The results of the measurements were also entered in this q(n) graph. The overloaded cable represents a "BAD" cable, whereas the correctly loaded cables represent "GOOD" cables.

The q(n) graphs with the results of both cables are shown in Figure 6.4. It is clearly seen that the overloaded cables suffer from higher numbers of discharges (both in magnitude and in repetition rate) than the cables that were loaded correctly. The line \( nq \leq 0.5 \text{ nC \cdot min}^{-1} \) fits well between the results of the overloaded cables and the correctly loaded cables and serves as a demarcation between these cables.

Following these two points, it is stated that, as a first proposal for HVDC mass impregnated paper cables, no discharges are allowed which exceed a limit of \( nq = 0.5 \text{ nC \cdot min}^{-1} \) during the first four hours after the cessation of the load\(^{28}\).

**Dielectric current test**

To add a dielectric current test has been previously proposed [55]. The current through the insulation consists of a leakage current and a polarization current. It should be recorded during stage II, after the external voltage has been stabilized (Figure 6.5). The current plotted as a function of time

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\(^{27}\) A MIND cable has a maximum safe operating temperature of 50 to 55°C. Above this temperature dry spots in the insulation may occur due to compound migration. These spots weaken the cable.

\(^{28}\) The requirement is restricted to the four hours every cycle for practical reasons. Requiring DC discharge tests during the whole stability test would have a large impact on laboratory work. Interference pulses may occur, for instance, if an impulse test is being performed in another part of the laboratory. To overcome this, the laboratory would have to be electrically quiet for 30 days. This is almost impossible. The requirement is therefore restricted to the most severe part of the test: the first four hours after cessation of the load.
is characteristic for the type of insulation. The current test during the type test may serve as a guide for the routine test in qualifying a manufactured cable [55].

Loss angle test
The loss angle is measured using an AC voltage. The loss angle has no direct relation to the operation of the cable at DC voltage. It serves, however, as a measure for the quality of impregnation. Just as the current test, the loss angle test may serve here as a guide during a routine test in qualifying a manufactured cable [55]. A loss angle test is already part of the ELECTRA 72 document, as a routine test.

6.3 Routine test
The routine test is performed on a full manufacturing length. Some tests, however, can be performed on limited lengths only, for reasons that will be explained later. In those cases, the tests should be performed on one or more representative cable pieces, for instance, 100 metres long. These tests are marked with the # sign in the enumeration of the test programme.

The proposed tests should be performed at ambient temperature only.

Tests marked with an asterisk* are new and cannot be found in the ELECTRA 72 document. Details concerning the techniques of performing the tests not marked with an asterisk can be found in the ELECTRA 72 document.

Test programme
- Conductor resistance test
- Capacitance test
- Loss angle test
- Dielectric current test
- Voltage test. A negative\(^{30}\) voltage of 2U\(_0\) shall be applied for 15 minutes.

---

\(^{29}\) Refer to §6.1, in which the definitions are given.

\(^{30}\) The polarity of the voltage during the voltage test is in fact arbitrary. However, as the probability of a flashover at a termination is smaller when using a negative voltage, it is preferable to use negative voltages during routine tests.
"*" Partial discharge test. Partial discharges shall be measured during the cessation of the voltage: stage IV.

Requirement: \[ nq \leq 2 \text{nC.min}^{-1} \quad \text{or} \quad Q \leq 50 \text{nC} \quad (Q = \sum_q q) \]

As the loss angle test, the dielectric current test and the partial discharge test are all recommended to be performed on a limited length of cable (for instance 100 m); these tests can be performed on the same cable piece.

Details of this proposal are considered below.

Conductor resistance and capacitance test
The conductor resistance test qualifies the manufactured conductor. The resistance per metre cable shall comply with the specifications. The correct dimensions of the cable insulation are checked by using the capacitance test, as the capacitance of a metre cable depends on the inner and outer radia of the insulation.

Loss angle test
The loss angle is a measure of the quality of the impregnation as explained in §6.2. The results of a loss angle test of a manufacturing length shall comply with the specifications and with the values as measured during the type test.

In general, the test can be performed on a limited length of cable only, as the AC loading current becomes too high for large lengths. Therefore, a length of at least 10 meters [22], but preferably 100 metres, shall be cut off a manufacturing length and shall be used for the loss angle test.

Dielectric current test
The current profile, \( i(t) \), shall be measured as is required in the type test. The profile shall not differ, for instance, more than 10 or 20% from the profile measured during the type test, as proposed by [55] (see Figure 6.6).

It should be noted that a temperature and a length effect exists.

![Figure 6.6](Image)

**Figure 6.6** The permitted deviation of the current versus time graph during the routine test as compared with that during the type test.
6.3 Routine test

The temperature influences the conductivity $\sigma$ and the time constant $\tau$ of the dielectric and will therefore change the current profile. The higher the temperature, the more compressed the profile will be in time and the higher the value of the current (see Figure 6.7).

It is therefore recommended to perform the current test during the routine test at the same ambient temperature as that of the current test during the type test.

When comparing the results of the routine tests with those of the type test, it is important to realize that the magnitude of the current is proportional to the length of the cable.

It is difficult to test a complete manufacturing length. The raising of the voltage will take a long time (order of magnitude $1/2$ hour) due to the limited power of the source. During the increase of the voltage, the current profile will already manifest itself. The current profile will then be distorted due to the slow increase of the voltage. It is therefore proposed to perform the dielectric current test on a limited length of cable, for instance, 100 metres. As this length is needed for the loss angle test anyway, this is no drawback.

Partial discharge test

It is hard to measure partial discharges on the extremely long manufacturing lengths (30 km) that are common today. Discharges far away from the detecting site will be heavily attenuated. This will distort the evaluation of the discharges. In addition, the sensitivity of the measurement will be low [57], due to the high capacitance of the long length of the cable. For this reason, the partial discharge test shall be performed on a limited length (for instance, 30 to 100 metres, as described in §6.1). The same cable piece as used for the dielectric current test and the loss angle test may be used.

It is logical to perform the partial discharge test at a stable voltage, stage II. However, the observations on HVDC cables, made by the author, led to the conclusion that measuring during stage II did not give enough power to discriminate between good and bad cables. The reason was that, generally, the repetition rate $n$ of the unloaded cables during this stage was too low at ambient
temperatures of 15 to 20°C. The number of detectable discharges was not large enough to make a safe evaluation of the results. This problem could be solved by heating the cable, thus increasing the repetition rate (see equation 3.20). However, there is an easier solution, as will be shown.

Far better results were gained when testing during the beginning of stage IV, after the cessation of the voltage. The overloaded cable (type B), as described in §6.2, was tested during this stage, as well as two cables (type A and B) in a virgin state. The deliberately overloaded cable, which failed later on during a shortened type test, represented a badly manufactured cable. The testing was performed in the following manner:

- The voltage of the cable was first raised to -350 kV.
- The source was kept stable at that voltage for 10 minutes, after which it was switched off. As a result, the voltage decreased with a slope determined by the capacitance of the cable and the discharging resistance (this can be the internal resistance of the voltage source (see a in Figure 6.8) or a special discharge resistance (b). In this work the internal resistance of the voltage source was used). The resulting time constant of the decreasing voltage was approximately 1 minute. Partial discharges were measured after the cessation of the voltage, starting at \( t=0 \) and ending at \( t=6 \) min.

\[
\tau_c = \frac{R_{\text{internal}}}{C}, \quad \tau_d = \frac{R_{\text{discharge}}}{C}
\]

**Figure 6.8** Discharging the cable using the internal resistance of the voltage source (①), or using a special discharging resistance (②).
The results are shown in Figure 6.9. As can be seen from the figure, a good discrimination between the overloaded cables and the virgin cables (read: the good and the bad cables) is possible. Few results of the virgin cable are presented as most of the measurements remained below the sensitivity level (see Figure 6.9). The difference in repetition rates of good and bad cables is a factor 100 to 10,000. The proposed requirement of $nq \leq 2 \text{nC min}^{-1}$ is drawn in the picture as a solid line.

Another advantage of this test is that the results are independent of the temperature, as the repetition rate of the discharges is no longer determined by temperature-dependent recharging of the voids, but by the slope of the decreasing external voltage.

This raises another problem: the repetition rate depends on the slope of the decreasing voltage, as this time constant depends on the length of the cable and the discharging resistance. A slope that is 10 times steeper results in a repetition rate that is 10 times higher. This in turn leads to a shift in the q(n) graph to the right by a factor 10.

It would, of course, be better to define a test that is independent of the time constant of the decreasing voltage. This is possible with the following method.
- Measure the discharges during stage IV starting from the decrease of the voltage at $t=0$ as discussed earlier.
- Stop recording the discharge when the voltage has decreased to a certain value,

![Figure 6.9 Results of discharge tests during the beginning of stage IV on virgin cables and overloaded cables in relation to the proposed requirement.](image)

![Figure 6.10 To use the total charge number $Q$ one should evaluate the discharges during the decrease of the voltage, for instance, between $V$ and 0.1V.](image)
for instance to 10% of the starting value: 0.1 V (see Figure 6.10). Integrate all the recorded discharges using

\[ Q = \sum q_i. \] (6.2)

- Cables with a total charge \( Q \) larger than a certain value will be marked "BAD", whereas cables with a value of \( Q \) lower than a certain value will be marked "GOOD".

The reason for recording the discharges between \( V \) and 0.1V, is that the voltage will decay exponentially. The decay of the last kilovolts will take too much time. Disregarding the few discharges during the decay of the last kilovolts will not influence the decision on the quality of the cable.

What remains is the determination of the decisive value of the total charge \( Q \). For this purpose, the test results, as shown in Figure 6.9, were used to calculate the total charge \( Q \). The results are shown in Figure 6.11.

A good discrimination between the "GOOD" and the "BAD" cables is possible. A decisive limit for the total charge \( Q \) may be 50 nC. Cables with a resulting total charge larger than 50 nC will be called "BAD", whereas cables with a resulting total charge smaller than 50 nC will be called "GOOD".

It is important to realize that the results of \( Q \) depend on the test sensitivity and on the maximum discharge that can be recorded. Small discharges will be disregarded if the sensitivity is low and will lead to a lower \( Q \). The higher the maximum discharge that can be registrated is, the higher is the total charge \( Q \). Therefore, the sensitivity and the maximum possible discharge that can be registrated should be mentioned when fixing the decisive value for \( Q \) and when

![Figure 6.11 Calculated total charge \( Q \) of virgin and overloaded cables during a decrease of the voltage from 1V to 0.1V. The sensitivity was 15 pC and the maximum discharge that could be registrated was 650 pC.](image)
evaluating test results. In this case, the sensitivity was 15 pC and the maximum discharge that could be registrated was 650 pC. The decisive figure of 50 nC is thus based on these testing boundaries.

It is concluded that we have two measures to discriminate between "GOOD" and "BAD" cables: the $nq$ criterium and the $Q$ criterium. Both criteria can be used. However, it is important to realize that

- the test, using the $nq$ criterium, depends on the length of the cable and the discharging resistance.
- the test, using the $Q$ criterium, depends on the measurement sensitivity and the maximum possible discharge that can be registrated.

### 6.4 Testing the factory joint

Routine tests on factory joints are not mentioned in the existing recommendations [22]. The manufacturing of a factory joint follows other steps than the manufacturing of a cable, but the factory joint shall have the same electrical, mechanical and thermal properties as the cable.

These statements argue for a routine test on factory joints too. As the factory joint should be seen as part of the cable, it seems logical to use the routine tests on cables as described in section 6.3.

Testing the complete delivery length, which includes the joints, would be another way of testing the joints. It is not proposed to test the joints in this way, but to test the joints seperately because of this length, as explained in §6.3.

**Test programme**

- Voltage test. A negative voltage of $2U_0$ shall be applied for 15 minutes.
- Partial discharge test. Partial discharges shall be measured after the cessation of the voltage: stage IV.
  - Requirement: $nq \leq 2$ nC·min$^{-1}$ or $Q \leq 50$ nC.

As a factory joint should have the same properties as the cable, the same requirements as used for the cable are proposed.

Some practical points regarding the separate testing of factory joints have to be considered. This will be done briefly.
The factory joints should be separated electrically from the rest of the cable, for reasons of sensitivity. If the joints were not separated from the cable, the complete cable would be tested. The longer the cable is, the lower is the sensitivity [57], as explained earlier. The best sensitivity can be reached by testing the joint only.

There are two methods of applying the voltage to the cable: the normal method and the inverse method (see Figure 6.12).

**Normal**
In the case of a normal voltage application, the high voltage is connected to the conductor and the sheath is earthed. The electrical separation of the joint from the cable may be relatively simple in its design.

The advantage of this method is the relatively simple set-up. The disadvantage of the method is that the complete cable is energized while, generally, part of the cable is still positioned in a factory machine. For safety reasons this may be a disadvantage.

**Inverse**
In the case of inverse voltage application, the high voltage is applied to the sheath of the joint only. The sheath of the rest of the cable and the conductor are earthed. The electrical separation of the joint and the cable must now be able to hold the complete test voltage and must be free of discharges.

The advantage of this method is that the part of the cable that is placed in the machinery is earthed. The test set-up is safer concerning the machinery. The disadvantage is the need for a more complex sheath interruption.

Only factory joints are routine tested. The field, repair and transition joints can be tested only on location. These joints are tested using the after-laying test that currently consists of a voltage test. Partial discharge testing at location, mostly on the ship, has many practical implications and is not feasible.
6.5 Factory acceptance test

As explained in §6.1, the factory acceptance test is performed on a delivery length. As such a length is generally very long (up to 100 km), it is not feasible to perform a loss angle test, a partial discharge test or a dielectric current test, for reasons explained in §6.3. Therefore, the proposed test programme does not contain these tests.

Test programme (according to ELECTRA 72)
- Conductor resistance test.
- Capacitance test.
- Voltage test. A negative voltage of $2U_0$ shall be applied during 15 minutes.

6.6 Conclusions

The following conclusions are drawn on the test requirements of an HVDC cable system of the mass-impregnated paper type:

1. There is incomplete knowledge concerning the life-line and the ageing of HVDC cables. The knowledge is sufficient for the current generation of cables, but might be insufficient for the development of a new generation cables.

2. The current recommendations of electrical tests on HVDC cables are based on overvoltage testing and heat cycling. Overvoltage testing is based on the life-line of the cable. As this knowledge is incomplete, diagnostic tests should be part of the electrical tests for the new generation of HVDC cables.

Type test
3. A partial discharge test is recommended as a new diagnostic test during the stability test.
4. The proposed requirement for partial discharge testing during this test is\textsuperscript{31}: 
\[ nq \leq 0.5 \text{ nC} \cdot \text{min}^{-1}. \]

5. A dielectric current test is recommended to be used during the type test. It will then serve as a guide for the routine test in qualifying a manufacturing length.

6. The samples should be type tested at the relevant ambient temperature. As a result, several samples may be type tested twice at different ambient temperatures.

\textit{Routine test}

7. A partial discharge test is recommendend as a new diagnostic test for new generations of HVDC cables. Because of the long lengths involved, it is recommended to perform the test on one or more \textit{representative lengths} of, for instance, 100 metres.

8. It is proposed to measure partial discharges during the beginning of stage IV (the decrease of the voltage). This gives a better discrimination between "good" and "bad" cables than during stage II (constant DC voltage).

9. Measuring the total charge \( Q \) at stage IV is introduced as a quality check. The number is independent of the ambient temperature and of the slope of the decreasing voltage during stage IV.

10. The proposed requirement for partial discharge testing during stage IV (routine test) is:
\[ nq \leq 2 \text{ nC} \cdot \text{min}^{-1} \]
or
\[ Q \leq 50 \text{ nC}. \]

11. The \( nq \) requirement depends on the slope of the decreasing voltage and, therefore, on the discharging resistance and the cable length. The \( Q \) requirement depends on the sensitivity of the measurement and the

\textsuperscript{31} These and next requirements are proposals based on the experiments described in this work. It is necessary to perform more discharge tests on different types of HVDC cables in different laboratories to check whether the requirements need some refinement. See also \S 7.2.
6.6 Conclusions

maximum possible discharge that can be measured.

12. A dielectric current test is recommended to be used during the routine test. The test shall be performed on one or more representative pieces of cable of, for instance, 100 metres. The results of the dielectric current test during the type test serves as a guide in qualifying the manufacturing length.

13. A loss angle test is recommended to be used during the routine test. The test shall be performed on one or more representative pieces of cable of, for instance, 100 metres. The results of the loss angle test during the type test serves as a guide in qualifying the manufacturing length.

Testing accessories

14. Accessories are recommended to be type tested according to ELECTRA 72 [22]. However, these recommendations do not mention a routine test to be performed on accessories. It is recommended to perform routine tests on accessories if possible.

15. As the factory joints must have the same properties as the cable and as the joints follow a partly different manufacturing process, it is proposed to apply the same tests and requirements as for the cable.

16. The other accessories, such as the field joint, the repair joint, the transition joint and the terminations are to be tested at the after-laying test only.
Proposals for test requirements
7.1 Conclusions regarding mass-impregnated HVDC cables

*Electric fields*

1. A model has been built that is capable of calculating electric field and charge distributions in a mass-impregnated cable in every voltage stage as defined in §2.1. The model simulates the well-known field inversion in a loaded mass-impregnated cable, see curve $C$ in Figure 7.1. By taking the field dependency of the paper conductivity into account, it has been found that the maximum field at $M$ may be up to 30% lower than that found when only the temperature dependency is taken into account. This result is of great interest for the design of HVDC cables.

The model also covers impulses superimposed on a DC-voltage as well as field calculations taking into account insulation losses.

*Figure 7.1* $A = $ DC field distribution in a cold cable. $B = $ ibid in a loaded cable, only the temperature dependency of the conductivity has been taken into account only. $C = $ ibid in a loaded cable, the field dependency of the conductivity has been taken into account as well.
2. If a cable is operated at a low environmental temperature (deep-sea cable), the field after polarity reversal decays more slowly than in the case of higher ambient temperatures (land cable), see Figure 7.2.

When partial discharges arise, after about half an hour these discharges act then in a higher electric field, so that polarity reversal is considered to be more severe for tests at a low ambient temperature.

3. Thermal breakdown of an HVDC cable is usually not expected. However, if the lead-sheath temperature is high enough (> 60 - 70°C), the leakage current of an HVDC cable may become sufficiently high to heat the insulation and to lead to a type of thermal breakdown. This might be of interest in respect to oil-filled cables which are operated and tested at far higher temperatures than mass-impregnated cables.

**Partial discharges**

4. The discharge repetition rate $n$ of a mass-impregnated HVDC cable shows two characteristic maxima after switching off the load, see Figure 7.3.

The first maximum $A$ represents pre-existing voids that discharge due to a sudden pressure drop of a few Bars adjacent to the conductor.

The second maximum $B$ represents the growth of voids due to the contraction of the cooling compound.
5. The results of discharge tests fit well in a $pC$-$\text{min}^{-1}$ diagram as proposed by [55]. Good and bad cables can be well distinguished in this way, as shown in Figure 7.4.

6. Nanocoulomb discharges, in the above diagram, are considered to be detrimental to the cable. Most probably they represent surface discharges between successive paper layers adjacent to butt-gaps.

\textit{Space charges}

7. The space charge behaviour of mass-impregnated paper is far more predictable than hitherto has been found for polymeric dielectrics. The charge distribution is surprisingly independent of variations in oil, paper or electrode materials.

Three phenomena have been found:

- Homocharge accumulates, regardless of the type of oil or paper that is used and regardless of the electrode polarity or electrode material (aluminum, copper, iron, carbon paper).

- The growth and decay of the homocharge can be described roughly by two time constants. First, a small time constant ($\leq 1$ minute) occurs, followed by a second, larger, time constant ($\geq 30$ minutes).

- The growth and decay of the homocharge distribution follows specific patterns. Immediately after a DC voltage is put over the sample, homocharge travels, as it were, from the electrodes into the paper, see Figure 7.5. After a while, the

\textbf{Figure 7.4}  

\textbf{Figure 7.5} The specific growth and decay patterns of homocharge.
charges reach the middle of the paper and the homocharge distribution occupies the complete sample. When the voltage is removed, the homocharges diminish in magnitude but remain at their place. The shape of the distribution does not change, see Figure 7.5b.

8. A physical model was built on the basis of Schottky charge injection, ionic conduction and charge recombination. The model predicts (1) the occurrence of homocharge, (2) the specific growth/decay patterns, (3) the order of magnitude of the homocharge, (4) the order of magnitude of the field enhancement and (5) the order of magnitude of the large time constant. The model failed to predict the occurrence of two time constants.

The model is a solid confirmation of the soundness of the observations.

9. The result of homocharge accumulation is a field enhancement in the paper layer samples. Thin, highly impermeable paper types show lower field enhancements (4-20%) than thick, low impermeable papers (75-100%). Papers impregnated with a low resistive oil show lower field enhancements (5-30%) than those impregnated with high resistive oils (75-90%). These observations accord well with the choice of materials in actual HVDC cables.

10. When stacked paper layers are tested, it is concluded that (see Figure 7.6)
- homocharge that is injected from an electrode does not cross the paper borders.
- surface charges accumulate on paper/oil interfaces.

The charge and field enhancement are concentrated, as it were, in the papers near the electrodes. Improvement of the insulation construction
7.1 Conclusions

should therefore be sought in the layers near the conductor and the lead-sheath.

11. Space charge tests can be usefull for selecting the type of insulating paper and oil, or, in general, the type of insulating material. If the performance of a new insulating material has to be checked, it is cheaper and less time-consuming to perform space charge tests on the new sample material than to perform destructive high-voltage tests on several full-sized cables that are manufactured with that new material.

Proposed test rules and recommendations

12. The current test recommendations for HVDC cables are based mainly on overvoltage testing and heat cycling. The concept of overvoltage testing is based on the electric life-line of the cable. As the knowledge of the life-line of HVDC cables is incomplete, it would be desirable to add diagnostic tests to the test rules for new generations of HVDC cables.

13. It is recommended by the author to add a partial discharge test to the type and routine tests of new cables.

The type test:
The test shall be performed during the stability test. The proposed requirement for HVDC paper cables is:

no discharges during the stability test which exceed a limit of 0.5 nC·min\(^{-1}\) are permitted.

The routine test:
The test shall be performed on a limited length of cable during stage IV (during the decay of the voltage). The proposed requirements for HVDC paper cables are:

no discharges during the voltage decay which exceed a limit of 2 nC·min\(^{-1}\) are permitted.

or

the integrated discharges shall not exceed the limit of 50 nC.

14. It is recommended to use a dielectric current test and a loss angle test during the type and routine test. The results of measurements taken during the type test will serve as a guide for the corresponding results for routine testing.
15. In accordance with the latest CIGRE recommendations, samples shall be type tested at the relevant ambient temperature. From this, it follows that some samples may have to be type tested twice: both at a cold ambient temperature and at a high ambient temperature, simulating the conditions for an unburied deep-sea cable and a land cable.

16. A factory joint must have the same electrical, thermal, and mechanical properties as the cable. As a partial discharge test is performed on the cable during the routine test, it is recommended to perform also a partial discharge test on each factory joint. The same test requirements as for the cable shall apply.

7.2 Suggestions for further study

1. It is necessary to perform additional partial discharge tests on different types of HVDC paper cables in order to check the discharge requirements for type test and routine tests as here proposed.

2. In order to have an increased understanding of the space charge phenomena in impregnated paper(s), measurements should be performed with a better spatial resolution. This objective can be reached by increasing the resolution of the pulsed electroacoustic measurement (as has been used in this study), or by using the laser induced measurement method.
Conclusions and suggestions
APPENDIX

A

Pulsed Electro-Acoustic Method

In this appendix, an elaborate description of the pulsed electro-acoustic method, as introduced in §4.1, is given. The text is divided into seven parts.
(1) a section describing the physical set-up of the system,
(2) a section describing the external high voltage circuits.
(3) a section describing the acoustic wave generation.
(4) a section describing the acoustic wave travelling.
(5) a section describing the detection circuit.
(6) a section giving an error estimate of the measurement system.
(7) a section in which it is explained how to compensate for signal distortion and how to calibrate the system.

Dimensions
A drawing of the actual system is shown in Figure A.1. The top electrode containing $E_{l1}$, $R_c$, $R_t$ and $C_c$ is made of brass. The resistors and the electrode are embedded in epoxy resin. $R_c$ (5 MΩ) and $C_c$ (250 pF) are needed to decouple the DC source and the pulse source from each other. Resistor $R_t$ (50 Ω) is a terminating resistor and is necessary to avoid reflections of the high voltage pulse. $R_p$ (1 MΩ) is an extra resistor to protect the DC source. The DC source is a MERK generator with three ranges (0-10 kV, 0-30 kV and 0-100 kV) in both polarities. A pulse generator of the voltage wave type has been used, it can generate pulses of 0-2.5 kV with a minimum pulse width of 10 ns.
1. PVDF-β film
2. PVDF-α, 1 mm thick
3. Silicon rubber, 5 mm thick
4. PMMA holder
5. Wrapped aluminum foil balls, or semi-conducting tape
6. Aluminum electrode $E_{1}$, ground plate, 10 mm thick
7. Aluminum electrode $E_{1}$, 8 mm diameter, 8
8. Sample
9. Epoxy resin

The width of the high voltage pulse is important. The smaller the width $\Delta T$, the better the spatial resolution $r$ as follows from the equation (A.1):

$$r = v \Delta T$$  \hspace{1cm} (A.1)

where $v$ denotes the acoustic wave velocity in the sample.

In Figure A.2, this relation is worked out for mass-impregnated paper which has a wave velocity of about 2000 m/s. For a pulse width $\Delta T$ of 10 ns, this results in a spatial resolution $r$ of 20 $\mu$m.

In order to make good acoustical contact between the sample and $E_{1}$, the area of $E_{1}$ underneath the sample should be extremely smooth. In addition, the sample must be pressed at $E_{1}$ with the use of the screw construction to ensure good contact (see Figure A.1).

The combined voltage, pulsed voltage $U_p$ superposed on the DC voltage $U_{DC}$, must be made available over the sample. Therefore, the brass housing of the top electrode, which is at zero potential, must be connected to the ground plate $E_{1}$. This connection must be made as short as possible to avoid any distortion of the high voltage pulse. The connection of the
brass housing with $E_{l_2}$ is made with three little balls made of wrapped aluminium foil or pieces of semi-conducting tape ("S" in Figure A.1). Wrapped aluminium foil balls or semi-conducting tape are used because the different samples are never of the same thickness, with tolerances of several micrometers. The height of these balls or the tape is automatically adjusted by the pressure of mounting the top electrode.

The sensor and the first amplifier are placed in a sealed brass box underneath the ground plate $E_{l_2}$ in order to minimize any noise coupling. The sensor consists of a PVDF-$\beta$ (Polyvinylidene Fluoride) foil of 9 $\mu$m thickness. PVDF-$\beta$ is a material with piezoelectric properties. Properties of the sensor are listed in Table A.1.

<table>
<thead>
<tr>
<th>property</th>
<th>PVDF-$\beta$, 9 $\mu$m</th>
</tr>
</thead>
<tbody>
<tr>
<td>$d_{33}$ [pCN$^{-1}$]</td>
<td>17.5 $\pm$ 10%</td>
</tr>
<tr>
<td>$\epsilon_c$ [-]</td>
<td>11 $\pm$ 10% (f=50Hz - 100 kHz)</td>
</tr>
<tr>
<td>$E_{\text{breakdown}}$ [V/$\mu$m]</td>
<td>750 $\pm$ 20%</td>
</tr>
</tbody>
</table>

Table A.1. Some properties of PVDF-$\beta$.

Leaving the sensor, the wave is transmitted into a layer of PVDF-$\alpha$, which has no piezoelectrical properties. It has, however, the same acoustical characteristics as the sensor, so that acoustical reflection is prevented. The following layer of silicon rubber attenuates and delays the reflection at the final interface.

The thickness of the sensor is limited. If a pressure wave of width $\Delta T$ does not cover the full width of the sensor, the electrical conversion will be insufficient (see Figure A.3).
There is a simple relation between the thickness of the sensor and the pulse width $\Delta T$:

$$d < v \Delta T,$$

(A.2)

where $d$ stands for the thickness of the sensor and $v$ for the wave velocity in the sensor. With $\Delta T = 10$ ns, $v = 2000$ m/s, this means that the sensor must be thinner than 20$\mu$m. In this work, the width of the sensor was 9 $\mu$m.

Both sides of the sensor have an aluminium layer of tens of nanometers thick. The sensor is connected to the first amplifier A. The amplifier, a Tronotech W500K, has a stable gain of 30 dB in the frequency range of 1 kHz to 500 MHz. The input impedance is 50 $\Omega$. From here, the signal is transported to a second amplifier of the same type, resulting in a total amplification of 60 dB. The signal is then fed into a 400 Msamples/second digitizing oscilloscope (HP 54502A) with a single shot analogue bandwidth of 100 MHz.

The bandwidth of the oscilloscope should be larger than the bandwidth of the signal. The maximum bandwidth of any measured space charge signal is limited by the bandwidth of the stimulating high voltage pulse $U_p$, which was measured, and amounted to 40 MHz. The bandwidth of the oscilloscope is indeed higher than the bandwidth of the high voltage pulse.
Electric high voltage circuit

The high voltage circuit applies both the DC voltage and the high voltage pulse to the sample (see Figure A.1); it is shown in Figure A.4. $R_i$ denotes the internal resistance of the pulse generator, which is 50 $\Omega$. $R_i$ (50 $\Omega$) mounted in the top electrode is necessary to avoid reflection of the high voltage pulse. $C_i$ denotes the sample capacitance.

It is difficult to build a high voltage generator that produces short pulses in the order of 10 ns. Once the generator has been built, it is undesirable that the high voltage circuit distorts or attenuates the pulse. The magnitudes of the coupling capacitance $C_i$ and the series resistors $R_e$ and $R_p$ influence the pulse that will be available over the sample $C_s$. The values of the capacitances and resistors that can be used without substantially distorting the signal are derived below.

![Figure A.4 The equivalent circuit of the high voltage circuit.](image1)

![Figure A.5 The equivalent circuit of the external circuit concerning the pulse voltage.](image2)

To compute the response of the circuit on a high voltage pulse $U_p$, this source is replaced by the equivalent source $U_p'$ (see Figure A.4 - terminating resistor $R_i$ can be seen as part of the pulse source which is of the voltage wave type). The equivalent circuit is drawn in Figure A.5. The upgoing slope of $U_p'$ will be seen across $C_s$. The discharging of $C_s$ however, must happen much more slowly than the duration of $U_p'$ ($\Delta T$).

In other words, the time constant of this circuit on a changing $U_p'$ must be much larger than the duration of the high voltage pulse,

$$\tau_{\text{circ}}(U_p') = (R_e + R_p)(C_e + C_s) \approx (R_e + R_p)C_e > \Delta T.$$  \hspace{1cm} (A.3)

With $R_e = 5 \text{ M}\Omega$, $C_e = 250 \text{ pF}$ and a typical value for the sample capacitance $C_s$ of 15 pF, the time constant becomes 5 ms which is far larger than the used pulse width $\Delta T$ (10 ns). Thus, if condition A.3 is fulfilled no signal distortion will take place.
Furthermore, it has been checked that a large percentage of the pulse \( U'_p \) is available over the sample capacitance \( C_s \). The pulse voltage \( U'_p \) is divided by \( C_s \) and \( C_c \). With values given above it follows,

\[
U_x = \frac{C_c}{C_c + C_s} U'_p \approx U'_p
\]  \hspace{1cm} (A.4)

Almost the complete magnitude of the pulse voltage appears over the sample.

**Acoustic wave generation**

Once the high voltage pulse has been generated, acoustical (pressure) waves start travelling, they originate from internal charges and from the electrode charges (Figure A.6). Field lines of a field \( E \) that arrive at a perfect conductor meet a surface charge \( \sigma \) of the following magnitude:

\[
\sigma = \varepsilon_0 \varepsilon_r E. \hspace{1cm} (A.5)
\]

In the situation of Figure (A.6) charges \( \sigma_1 \) and \( \sigma_2 \) at electrodes \( El_1 \) and \( El_2 \) are then given by

\[
\sigma_1 = \varepsilon_0 \varepsilon_r E_1, \hspace{1cm} (A.6)
\]

\[
\sigma_2 = -\varepsilon_0 \varepsilon_r E_2, \hspace{1cm} (A.7)
\]

where \( E_i \) stands for the magnitude of the electric field at \( El_i \), \( E_i \) for the field at \( El_j \). The field acts on the electrode charges, resulting in mechanical forces per unit area, i.e. pressure,

\[
p_1 = \frac{1}{2} \varepsilon_0 \varepsilon_r E_1^2 = \frac{1}{2} \sigma_1 E_1, \hspace{1cm} (A.8)
\]

\[
p_2 = -\frac{1}{2} \varepsilon_0 \varepsilon_r E_2^2 = \frac{1}{2} \sigma_2 E_2. \hspace{1cm} (A.9)
\]
The field $E_i$ consists of a DC field generated by the DC source and a pulse field generated by the pulse source,

$$E_2 = E_{2,DC} + E_p,$$  \hspace{1cm} (A.10)

$$E_1 = E_{1,DC} + E_p,$$  \hspace{1cm} (A.11)

where $E_{i,DC}$ denotes the DC field at the corresponding electrode and $E_p$ stands for the pulse field, which is the same at both electrodes. Substituting (A.10) and (A.11) in equations (A.8) and (A.9) results in

$$p_1 = \frac{1}{2} \varepsilon_0 \varepsilon_r (E_{1,DC}^2 + E_p^2 + 2 E_{1,DC} E_p),$$  \hspace{1cm} (A.12)

$$p_2 = -\frac{1}{2} \varepsilon_0 \varepsilon_r (E_{2,DC}^2 + E_p^2 + 2 E_{2,DC} E_p).$$  \hspace{1cm} (A.13)

The term $E_{i,DC}$ represents a constant pressure, which can be neglected.

Using equations (A.6) and (A.7) results in

$$p_1 = \sigma_{1,DC} E_p + \frac{1}{2} \varepsilon_0 \varepsilon_r E_p^2,$$  \hspace{1cm} (A.14)

$$p_2 = \sigma_{2,DC} E_p - \frac{1}{2} \varepsilon_0 \varepsilon_r E_p^2.$$  \hspace{1cm} (A.15)

Generally $\varepsilon_0 \varepsilon_r E_p^2 \ll \sigma_{i,DC} E_p$, so that it follows that

$$p_1 \approx \sigma_{1,DC} E_p,$$  \hspace{1cm} (A.16)

$$p_2 \approx \sigma_{2,DC} E_p.$$  \hspace{1cm} (A.17)

The acoustic waves, originating from the electrodes, are therefore linearly proportional to the pulse voltage $U_p$ and to the electrode charges $\sigma_{i,DC}$.

The pulse field $E_p$ also acts on a slab of space charge $\rho$ of width $b = v \Delta T$ at place $x$ in the sample, where $v$ stands for the speed of sound in the sample. The pressure at place $x$ due to the space charge is then given by

$$p_3(x) = \rho(x) b E_p.$$  \hspace{1cm} (A.18)

It follows that the acoustic wave originating from the space charge is linearly proportional
to the pulse voltage $U_\rho$ and to the space charge $\rho$.

**Acoustic wave travelling**
The pressure waves that are received at the sensor are less in magnitude than the original pressure waves at the site of the charges where they were generated. This has two reasons.

(I) The pressure waves are attenuated by the sample material itself. The further they have to travel, the more they are attenuated. This attenuation is mostly frequency dependent. Li [66] used a numerical method to compensate for this effect. In this thesis, a compensating method is used, which assumes that the attenuation is independent of frequency (§4.3).

(II) Pressure waves that are generated at different places experience different transmission, reflection and generation coefficients while passing material interfaces. There are three different situations.

1 (1) A pressure wave originating from the electrode charge $\sigma_1$ is split into two halves differing in magnitude, one half travelling into the sample, the other into electrode $E_{l_1}$. Following the wave in the direction of the sensor, the wave is transmitted from the sample into electrode $E_{l_2}$ and after that into the sensor.

2 (2) A pressure wave originating from the electrode charge $\sigma_2$ is first split into two halves differing in magnitude, one half travelling back into the sample, the other into electrode $E_{l_2}$. From there on one wave is transmitted into the sensor material.

3 (3) A pressure wave originating from a space charge $\rho$ is first split into two equal halves, one travelling towards $E_{l_1}$, one travelling towards $E_{l_2}$. Following the wave in the direction of the sensor, the wave is transmitted from the sample into electrode $E_{l_2}$ and after that into the sensor.

In appendix B, we see the derivation where the magnitudes of the pressure arriving at the sensor are given by (neglecting the attenuation)

$$P_{1,\text{sensor}} = \frac{4Z_{\text{sensor}}Z_{sa}}{Z_{E_{l_1}}^2}p_1 = 0.1p_1,$$

(A.19)

where $p_1$ is the pressure wave generated by electrode charge $\sigma_1$ and $P_{1,\text{sensor}}$ the corresponding pressure wave arriving at the sensor. $Z_x$ stands for the acoustical impedance of material $x$.

For the wave originating from electrode charge $\sigma_2$, it is derived that

$$P_{2,\text{sensor}} = \frac{2Z_{\text{sensor}}}{Z_{E_{l_2}}}p_2 = 0.5p_2,$$

(A.20)
and for waves originating from a space charge ρ inside the sample

\[ p_{3,\text{sensor}} = \frac{2Z_{\text{sensor}}}{Z_{E1}} p_3 \approx 0.5 p_3. \]  \hspace{1cm} (A.21)

It can be seen from these equations that equal parts of the pressure waves originating from the electrode charge σ₁ and space charge ρ are received at the sensor. This is important, as the space charge ρ is calibrated with the electrode charge σ₂.

In a test, however, the electrode charge σ₁ will appear to be five times smaller than an equivalent electrode charge σ₂ and an equivalent space charge ρ (p₁, sensor = 1/5 p₂, sensor and 1/5 p₃, sensor). This must be remembered when interpreting the results. One can either disregard this electrode charge, as one is generally interested in the space charge only, or one may multiply the measured value by a factor five.

**Detecting circuit**

The sensor converts the acoustic signal \( p(t) \) into a voltage \( v(t) \). The conversion is frequency dependent. After this conversion, the signal of the sensor is received by a 500 MHz wide bandwith amplifier with an input resistance of 50 Ω.

The electric behaviour of the sensor-amplifier combination will be described, by using an equivalence circuit as drawn in Figure A.7.

The sensor itself must be replaced by an equivalent electric circuit and can be quite complicated [13]. In figure A.7, a simplified description is used. Li [66] checked the validity of this approach for the specific use of the sensor in the space charge detecting system. She checked the linearity of the pressure to voltage conversion both in time and magnitude.

![Figure A.7 The equivalent circuit of the detecting circuit.](image)

The sensor converts the pressure \( p \) to a voltage \( U_p \). The conversion factor can be calculated by using

\[ U_p(f) = \frac{d_{33} d}{\varepsilon_0 \varepsilon_r(f)} p, \]  \hspace{1cm} (A.22)

in which \( d_{33} \) is the piezo strain constant (see Table A.1), \( d \) is the thickness of the foil, \( \varepsilon_r(f) \) stands for the frequency-dependent permittivity of the sensor and \( p \) is the pressure signal. The higher the frequency is, the lower is the relative permittivity \( \varepsilon_r \).
This means that the higher frequencies are gained in favour of the lower frequencies. Pressures of 1 N/m² result in signals of several μV's. The sensor itself has a certain capacitance $C_{sensor}$. Together with the input resistance $R_i$ of the amplifier, it will act as a high pass filter. In the time domain, this results in a differentiating action for the lower frequencies. Figure A.8 shows the effect of the frequency-dependent $R_iC_{sensor}$ combination on a pressure signal $p(t)$ as a result of the response of an electrode charge.

![Diagram of deconvolution](image)

**Figure A.9** The principle of deconvolution. Ideally one could compute the distorted signal back to the original waveform. In practice, the situation is less ideal.

The electrical signal is not a correct representation of the space charge profile. Three effects are taken into consideration.

1. We have seen that the RC filter action of the detection circuit has distorted the original pressure signal.
2. The conversion by the foil is frequency dependent (see equation (A.22)).
3. In addition, any slab of charge smaller in width than $s = vΔT$ is still measured as a slab of charge of width $s$, because of the minimum width of high voltage pulse $U_p$. For instance, the electrode sheet charges $q_1$ and $q_2$, which are believed to be very thin ($\ll 20$ μm), are still depicted as chargelsabs of width $v_{num}ΔT = 20$ μm. The effects are shown in Figure A.10. These three effects are combined under the name system response $H$. The system response gives the relationship between the signal at the oscilloscope and the space charge in the sample. If the system response is known, it would be possible to compute the original space charge profile by using the inverse system response $H^T$ (see Figure A.10). Ideally, this would result in the original space charge signal disposing of the RC filtering and the frequency dependent sensor response and would result in a very high resolution (the dotted $H^T$ in Figure A.10). In this work, the effect of the RC filtering and the frequency-dependent sensor response were eliminated, but the resolution did not improve. The enhancement in the resolution is limited by the presence of noise in the signal.
Standard text books on circuit theory and signal theory [81] explain the convolution theorem and system response in general. The convolution theorem\textsuperscript{32} states, that once the signal response of a linear circuit is known, the relation between the in- and output of that circuit can be calculated. In our case, it means that the space charge signal $\rho(t)$, the pressure signal $p(t)$, the high voltage pulse $U_p(t)$, the detection circuit response $h_{\text{circuit}}(t)$ and the electric output signal $v_s(t)$ are linked in the following way,

$$v_s(t) = K h_{\text{circuit}}(t) \otimes [U_p(t) \otimes \rho(t)] = (U_p(t) \otimes \rho(t) = p(t)), \quad (A.23)$$

and in the frequency domain,

$$v_s(f) = K h_{\text{circuit}}(f) U_p(f) \rho(f) = K H(f) \rho(f), \quad (A.24)$$

in which $H(f)$ denotes the total system response in the frequency domain and $K$ is a calibration factor.

The original space charge profile may now be calculated by a simple algebraic division in the frequency domain and an inverse Fourier transformation $\mathcal{F}^{-1}$,

$$\rho(t) = \mathcal{F}^{-1}[\rho(f)] = \frac{1}{K} \mathcal{F}^{-1} \left[ \frac{v_s(f)}{H(f)} \right] = \frac{1}{K} v_s^{\text{decon}}(t), \quad (A.25)$$

in which $v_s^{\text{decon}}(t)$ is the electric output signal in the time domain after deconvolution. A problem that may occur in using equation (A.25) is that the function $H(f)$ may be very small (noise), or even zero for some frequencies. Then the division in the frequency domain becomes impossible. The exact use of equation (A.25) is outlined in Appendix C.

To perform the above procedure, the response function $H(f)$ must be known. This is done by using equation (A.24). Once an electric signal $v_s$ as a result of a KNOWN space charge distribution $\rho$ is measured, the response function $H$ can be calculated. The only space charge distributions that can be predicted exactly are the electrode charges $\sigma_1$ and $\sigma_2$ according to equations (A.6) and (A.7). Electrode charge $\sigma_2$ is taken instead of $\sigma_1$, because the acoustic

\textsuperscript{32} Convolution theorem:

$$a(t) = \int_{0}^{t} h(\tau) b(t-\tau) d\tau = h(t) \otimes b(t)$$

$$\mathcal{F}(a(t)) = A(f) = h(f)b(f).$$

The response function $h(t)$ links the input signal $b(t)$ with the output signal $a(t)$, using the integral form denoted by the symbol $\otimes$. In the Fourier domain, the relation becomes a simple algebraic multiplication.
signal of this charge has not experienced any attenuation and dispersion by the sample material. The signal \( v_{s, E_2}(t) \), as a result of the electrode charge \( \sigma \), is then measured. The electrode charge is generally believed to be very thin [69] and, therefore, equation (A.24) can be rewritten as

\[
H(f) = \frac{v_{s, E_2}(f)}{K \rho_{E_2}(f)} = \frac{v_{s, E_2}(f)}{K \sigma_2} = \frac{1}{K_1} v_{s, E_1}(f),
\]  

(A.26)

in which \( K_1 \) is a constant and the relation \( \rho_{E_2}(f) = \mathcal{F}[\sigma_2 \delta(t)] = \sigma_2 \) has been used. Here \( \delta(t) \) denotes the impulse function known from signal theory.

The procedure can also be found in [69]. More details about the calculation and the effect of the response function \( H \) can be found in Appendix C.

**Calibration**

The electrical output signal \( v_{s, \text{decon}}(t) \), in mV's that has been treated as outlined above must be converted into \( C/m^2 \), the unit of charge density. It is assumed that the high voltage pulse \( U_p \) is square. Using equation (A.18) it is stated that,

\[
v_{s, \text{decon}} = \kappa p = \kappa E_p b p = K \rho.
\]  

(A.27)

The calibration factor \( K \) can be calculated if a KNOWN charge distribution is measured. We again use the electrode sheet charge \( \sigma_2 \). The procedure is as follows.

A DC voltage \( U_{DC}^{\text{cal}} \) is put across an initially space charge free sample. The electrode sheet charge \( \sigma_2 \) can then be computed using equation (A.7),

\[
\sigma_2^{\text{cal}} = \varepsilon_0 \varepsilon_r \frac{U_{DC}^{\text{cal}}}{d}.
\]  

(A.28)

Using equation (A.27) and

\[
P_{2, \text{cal}} = \varepsilon_0 \varepsilon_r U_{DC}^{\text{cal}} E_p \frac{U_{DC}^{\text{cal}}}{d}.
\]  

(A.29)

it then follows that

\[
K = \frac{d b}{\varepsilon_0 \varepsilon_r} v_{s, \text{cal}} = Ab \frac{v_{s, \text{cal}}}{C U_{DC}^{\text{cal}}},
\]  

(A.30)

in which \( d \) denotes the thickness of the sample, \( C \) the sample capacitance, \( A \) the sample area under high voltage, \( U_{DC}^{\text{cal}} \) the DC voltage during calibration and \( v_{s, \text{cal}} \) the signal after
deconvolution as a response to the calibration electrode charge $\sigma_2$. If the high voltage pulse $U_p$ is not completely square, one should use the integral form, which in the approximation leads to

$$v_{\text{sound}} \int_{v_{\text{s,cal}}}^{v_{\text{decon}}} \Delta T v_{\text{decon}}(t) \, dt = v_{\text{sound}} \Delta T v_{\text{decon}}(t) = b v_{\text{decon}}.$$  \hspace{1cm} (A.31)

The integral form would then be a more accurate way to calibrate. Equation (A.31) should be substituted in equation (A.30).

**Error estimation**

The results from the electro-acoustic system contain an uncertainty. The uncertainty is evaluated in this section. Therefore, every conversion step in the system is evaluated on its systematic and statistical error.

![Diagram](image)

**Figure A.10** The conversion steps in the electro-acoustic system during testing and calibration. OBSERVE: During a calibration the same conversion steps are made as during a normal test.

**First** a measurement is made (left part of Figure A.10).

1. The conversion from charge to pressure is assumed to be independent of temperature and time within the normal range of testing. Therefore, it is stated that no statistical errors of importance occur in the conversion from charge to pressure. As the conversion is exact, no systematic error occurs either.
While travelling through the sample, the pressure wave is attenuated. The attenuation is assumed to be independent of temperature and time within the normal range of testing. Therefore, it is stated that after attenuation no systematic and statistical errors of importance have occurred.

In the conversion from pressure to an electric signal, noise is introduced. This noise is due to the electromagnetic incoupling and due to the thermal noise of the sensor. The noise is superimposed on the electric signal and influences the result each time when measuring. It results in a statistical error. The noise distribution is normally constant in magnitude, therefore, the larger the signal is, the smaller is the statistical error. It is assumed that no systematic error occurs.

The electric signal is amplified. Again, noise is introduced, thus resulting in a statistical error. The amplifier has a systematic error of 0.5%.

The signal is digitized in the oscilloscope. The accuracy of the oscilloscope is independent of temperature and time within the normal range of testing. Therefore, no statistical error of importance is introduced. A systematic error due to the analog-to-digital conversion will occur, and it is smaller than 0.5%.

The digitized signal is subjected to a deconvolution procedure in the computer. Deconvolution is a numerical process that uses much computing power. A systematic error will occur due to the rounding-off error during the computing. The deconvolution program was written using MATLAB software, which uses an accurate means of matrix computation, which limits the rounding-off errors as much as this is possible. The error was estimated by using a small computer program, and it is very much less than 0.01%.

The computation is independent of time and temperature, so the statistical error is set to zero.

The final result is read from the computer using a 15 digit format. The error in reading is, therefore, negligible.

Next, the system is calibrated (right part of Figure A.10). Two steps are now important. (1) The calibration is done using a test result that has gone through the same conversions as those described above. The calibration links the result in \( mV/s \) to the actual charge density in \( C/m^3 \) using the calibration factor \( K \). This is shown with an arrow in Figure A.10. The calibration passes all conversion steps thus ruling out every systematic error.

The error in the calibration is now determined completely by the uncertainty in the parameters of the calibration factor \( K \), according to equation (A.30). All these parameters must be measured and errors will occur. The error in measuring the sample capacitance \( C \) is 1%, the error in the DC voltage \( U_{dc} \) is 1.5%, the error in the width of the high voltage pulse \( \Delta T \) is 2%, the error in the wave speed in the sample \( v \) is 5% and the error in the sample area under high voltage \( A \) is 1%. As all these parameters are uncorrelated, it is permissible to add the errors of all these parameters, and the systematic errors as mentioned under points (4) and (5) which results in a systematic calibration error of about 12%.

(2) For every test after the calibration, the statistical error remains. As explained, the statistical error is mainly a result of uncorrelated noise. There are two situations in which the effect of the noise can be reduced.
First, the error due to this noise will become less if the actual signal is large compared to the noise, i.e., if the signal-to-noise ratio becomes large.

Second, the effect of the noise will be reduced when averaging over a certain number of sub-tests (shots). This method of reducing the noise has been used throughout this work. Every test result was derived from an averaging over a series of shots. This was done by using the average modus of the oscilloscope. The higher the averaging number is, the lower is the statistical error.

A test was performed to determine the statistical error as a function of the averaging number and the scale of the oscilloscope. The test procedure was as follows.
- A PE sample was placed in the equipment.
- The DC source $U_{dc}$ was adjusted in such a way that the result could be measured in the 10 mV scale of the oscilloscope.
- Ten tests were performed one after the other, each consisting of 16 shots. This resulted in ten results.
- More tests were done using combinations of oscilloscope scales (10, 50 and 200 mV) and averaging numbers (16, 64 and 256).

The relative statistical error is given by [79]

$$ statistical\ error = \frac{\mu S}{\mu \sqrt{n}} \quad (A.32) $$

in which $n$ is the number of tests (10), $\mu$ is a factor of the Student distribution and equals 2.26 for a degree of freedom of $n-1=9$ and a confidence level of 95%, $S$ is the standard
deviation\textsuperscript{33} and \( \mu \) is the average of the 10 measurements. The statistical error is shown in Figure A.11.

The figure shows that most of the noise is removed when using an averaging number of 64. Higher averaging numbers will not yield better results. The most often used averaging number was therefore 64. Small space charges of 1 to 5 C/m\(^3\) were measured in the 10 mV per division range of the oscilloscope. The more often occurring values of 10 C/m\(^3\) and higher were measured in the 50 to 200 mV per division ranges of the oscilloscope. The statistical error was normally 1\%, but never more than 3\%, as follows from Figure A.11.

The total error, according to equation (A.33) [79],

\[
\text{total relative error} = \text{relative systematic error} + \text{relative statistical error} \quad (A.33)
\]

was normally 12+1=13\%.

It is concluded that the total error of measurement using the pulsed electro-acoustic system is about 15\%.

When a number of paper samples of the same type and batch are measured, still different values of homocharges are found. These differences are due to unknown physical and chemical differences per sample. This difference is named the physical scatter.

The physical scatter, which is usually in the order of 50\% (in extreme cases 150\%), is larger than the estimated error as derived above. It is, therefore, of no use to improve the accuracy of the electro-acoustic system for testing paper samples.

\textsuperscript{33} The standard deviation \( S \) is defined as

\[
S = \sqrt{\frac{\sum_{i=1}^{N} (x_i - \mu)^2}{N-1}}
\]

where \( x_i \) is a value out of a set of \( N \) values and \( \mu \) is the average of the \( N \) values.
APPENDIX

B

Acoustic wave travelling

This appendix describes two subjects concerning the acoustic wave travelling:
(1) The fraction of an acoustic wave arriving at the sensor due to reflection, transmission and generation coefficients is derived. The results are used in appendix A. Attenuation of the wave solely by the sample material is not considered here.
(2) The minimum thicknesses of the aluminium electrode $E_{L_2}$ and the backing layers necessary to avoid reflections that could disturb the measurement signal are derived.

Effect of transmission, reflection and generation coefficients
The acoustic waves are considered to be plane waves. In this case [13], this description is analogous to the electric plane wave theory. The waves are reflected and transmitted according to the difference in the acoustic impedances of the different media,

$$ R = \frac{Z_1 - Z_2}{Z_1 + Z_2} \quad (B.1) $$

$$ T = \frac{2Z_2}{Z_1 + Z_2} \quad (B.2) $$

$$ G = \frac{Z_1}{Z_1 + Z_2} \quad (B.3) $$

in which $R$ stands for the reflection coefficient, $T$ the transmission coefficient, and $G$ the generation coefficient, if the acoustical wave originates from a source placed exactly at the interface of two media. $Z_1$ is the acoustical impedance of the medium from where the wave is originating, whereas $Z_2$ denotes the acoustical impedance of the medium to where the wave is travelling.
The acoustical impedance is given by

$$Z = \rho v_m,$$  \hspace{1cm} (B.4)

where $\rho$ stands for the specific density of the medium and $v_m$ for the velocity of sound in the medium. Table B.1 gives a summary of acoustical properties of different materials [66].

<table>
<thead>
<tr>
<th></th>
<th>Aluminium</th>
<th>PVDF-$\alpha,\beta$</th>
<th>mass impregnated paper</th>
<th>LDPE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sound velocity [m/s]</td>
<td>6400</td>
<td>2200</td>
<td>2000</td>
<td>2000</td>
</tr>
<tr>
<td>Specific density [kg/m$^3$]</td>
<td>2700</td>
<td>1800</td>
<td>700-1100</td>
<td>900</td>
</tr>
<tr>
<td>Acoustical impedance [10$^6$ kg/ms]</td>
<td>17</td>
<td>3.9</td>
<td>1.4-2.2</td>
<td>1.9</td>
</tr>
</tbody>
</table>

Table B.1. Some acoustical properties of materials.

The electrode charges $\sigma_1$, $\sigma_2$ and the space charge $\rho$ all experience different transmission, reflection and generation coefficients (see Figure B.1). The fractions of the pressure waves that arrive at the sensor are calculated below.

Figure B.1 The principle of transmission and reflection of acoustic waves within the electro-acoustic measurement set-up.
The fraction of the acoustic wave originating from $El_1$ that arrives at the sensor is given by

$$\frac{P_{1,\text{sensor}}}{P_1} = G_1 T_2 T_3 = \frac{Z_{sa}}{Z_{sa} + Z_{Al}} \frac{2Z_{Al}}{Z_{Al} + Z_{sa}} \frac{2Z_{\text{sensor}}}{Z_{\text{sensor}} + Z_{Al}} = \frac{4Z_{\text{sensor}} Z_{sa}}{Z_{Al}^2} = 0.1.$$ \hspace{1cm} (B.5)

The fraction of the acoustic wave originating from $El_2$ that arrives at the sensor is given by

$$\frac{P_{2,\text{sensor}}}{P_2} = G_2 T_3 = \frac{Z_{Al}}{Z_{Al} + Z_{sa}} \frac{2Z_{\text{sensor}}}{Z_{\text{sensor}} + Z_{Al}} = \frac{2Z_{\text{sensor}}}{Z_{Al}} = 0.5.$$ \hspace{1cm} (B.6)

The fraction of the acoustic wave originating from the space charge that arrives at the sensor is given by

$$\frac{P_{3,\text{sensor}}}{P_3} = \frac{1}{2} T_2 T_3 p_3 = \frac{1}{2} \frac{2Z_{Al}}{Z_{Al} + Z_{sa}} \frac{2Z_{\text{sensor}}}{Z_{\text{sensor}} + Z_{Al}} = \frac{2Z_{\text{sensor}}}{Z_{Al}} = 0.5.$$ \hspace{1cm} (B.7)

The transmission and generation parameters were calculated using Table B.1. As can be seen from equations (B.6) and (B.7), the fractions of the two acoustic waves originating from the earthed electrode $El_2$ ($p_{2,\text{sensor}}/p_2$) and from the space charge ($p_{3,\text{sensor}}/p_3$) are equal (0.5). The fraction of the charge originating from electrode $El_2$, denoted by $p_{1,\text{sensor}}/p_1$, however, is five times smaller (0.1). In an actual test, the electrode charge $\sigma_1$ will appear to be too small. This must be remembered when interpreting measurement results. One can either disregard this surface charge or multiply it by a factor five.

**Thickness of aluminium electrode and backing layers**

Part of the acoustic waves are reflected between the $El_2$ - sensor interface and the sample - $El_2$ interface (see Figure B.1). The reflection will, after some time, appear for a second time at the sensor. This reflection must not arrive at the sensor before the acoustic waves of the complete sample have passed the foil. This means that

$$\frac{2d_{Al}}{v_{Al}} > \frac{d_{sa}}{v_{sa}}.$$ \hspace{1cm} (B.8)

In this work, the electrode thickness $d_{Al}$ was 10 mm. Using a paper sample thickness $d_{sa}$ of 200 $\mu$m, the inequality becomes $3.1$ $\mu$s $>$ 0.1 $\mu$s and is fulfilled. According to equation (B.8), the maximum paper sample thickness that could be tested safely was 6.3 mm.

Leaving the sensor, the acoustic waves are transferred into a PVDF-$\alpha$ backing which has the same acoustical properties as the sensor (see Figure B.1). Therefore, no reflection occurs, but there is total transmittance.
However, the waves are reflected at the PVDF-α - silicon rubber interface. Here also, it can be stated that this reflection must not arrive at the sensor before the acoustic waves of the complete sample have passed the sensor. This means that

\[
\frac{2d_{PVDF-\alpha}}{v_{PVDF-\alpha}} > \frac{d_{sa}}{v_{sa}} \tag{B.9}
\]

In this work, the thickness of the PVDF-α was 1 mm. Using a paper sample thickness \(d_{sa}\) of 200 \(\mu\)m, the inequality becomes 1 \(\mu\)s > 0.1 \(\mu\)s and is fulfilled. According to equation (B.9), the maximum paper sample thickness that could be tested safely was 2 mm.
APPENDIX

C

Deconvolution

If the deconvolution process is performed with the use of equation (A.25), two problems may occur. First, when the frequency content of the response function $H(f)$ contains zeros for some high frequencies, the division in equation (A.25) becomes impossible. This problem can be overcome by the use of a Wiener filter.

Second, when the frequency content of the response function $H(f)$ contains very small values for some high frequencies, the high frequency noise in the signal $v_r(t)$ will be amplified too much. This complicates the deconvolution process. This problem can be overcome by the use of a Gaussian filter that removes the high frequency noise from the signal.

The complete procedure is explained with the aid of Figure (C.1). The signal $v_{s, E_{12}}(t)$, in the figure, shows a measured signal that is a result of an electrode charge $\sigma_2$. Due to the fact that surface charge $\sigma_2$ is very thin, the signal $v_{s, E_{12}}(t)$ is equal to the response function of the electro-acoustic system in the time domain.

Signal $v_s(t)$ in the figure is the result of an arbitrary measurement and is the signal that has to be treated.

Both signals are converted to the frequency domain using an FFT (Fast Fourier Transform) algorithm. From there, $v_{s, E_{12}}(f)$ is filtered using a Wiener filter. The following relation holds for the Wiener filter

$$\frac{1}{h^w(f)} = \frac{v_{s, E_{12}}^*(f)}{|v_{s, E_{12}}(f)|^2 + a^*},$$

(C.1)

in which $v_{s, E_{12}}^*$ represents the complex conjugate of $v_{s, E_{12}}$ and $a$ is the Wiener filter constant which may lie somewhere between $1 \times 10^{-4}$ to $1 \times 10^{-6}$. This value is not critical. In this
signal to determine impulse response $v_{s, EI2}(t)$  \[ \xrightarrow{\text{FFT}} \]  $v_{s, EI2}(f)$  \[ \xrightarrow{\text{Wiener}} \]  $\frac{1}{h^w(f)}$  \[ \xrightarrow{\text{Multiply}} \]  $v_s\text{decon}(t)$

signal to be treated $v_s(t)$  \[ \xrightarrow{\text{FFT}} \]  $v_s(f)$

Gauss function $g(f)$  \[ \xrightarrow{\text{Multiply}} \]  $v_s\text{decon}(t)$

\[ \mathbb{M} = \text{multiply} \]

**Figure C.1** The actual procedure of the deconvolution. Every square shows a signal in the time- or frequency-domain. The name of the signal is written above each box, whereas the action that is taken, a FFT, a Wiener filtering or a multiplication, is written above each arrow.

thesis, a value of $1 \times 10^{-3}$ has been used.

From there on, the deconvolution is carried out:

\[ \frac{v_s(f)}{h^w(f)} \]  \[ \text{(C.2)} \]

The result is filtered with a Gaussian filter $g(f)$ [12] by multiplying $g(f)$ with the result of the deconvolution: equation (C.2). The absolute value of the Gaussian filter in the frequency domain is given by

\[ |g(f)| = \exp\left[\frac{-\ln2\left(\frac{f}{f_c}\right)^2}{2}\right], \]  \[ \text{(C.3)} \]

in which $f_c$ is the cut-off frequency of the filter. In this thesis, values for $f_c$ varying from 50 MHz to 70 MHz were used. The higher the value of $f_c$ is, the higher is the resolution. The use of higher values of $f_c$ is limited by the presence of noise in $v_s(t)$.
The response function $H(f)$ as used in Appendix A can thus be written as

$$H(f) = \frac{g(f)}{h_w(f)}.$$  \hfill (C.4)

In Figure C.2, an example of the beneficial effect of the use of the response function is shown. Electrode charge $\sigma(t)$ is measured using a 50 ns-wide high voltage pulse $U_p$.

The pressure pulse $p(t)$ inside the sample has the same shape as the voltage pulse. The effect of the impulse response of the measurement system is shown in the figure as $v_s(t)$.

With the use of the inverse response function $H^{-1}$, these effects are ruled out in $v_s^{\text{decon}}(t)$, and the original shape is almost completely restored.

---

**Figure C.2** An example of the power of the deconvolution technique in the time domain using the result of electrode charge $\sigma(t)$. The $\otimes$ symbol is the convolution operator in the time-domain.
APPENDIX

D

Insulation losses

In this appendix, the temperature drop $T_r - T_c$ at location $r$, inside the insulation of a cable that is due to heating by the leakage current $I_0$ is calculated ($T_c$ stands for the temperature of the conductor and $T_r$ is the temperature of the insulation at location $r$). The temperature drop due to the conductor losses is the well-known $\Delta T$, and is disregarded here.

The general equation of heat transfer in cylindrical coordinates in a stable situation ($\partial T/\partial t = 0$) is given by

$$\frac{1}{r} \frac{\partial}{\partial r} \left( r \frac{\partial T}{\partial r} \right) + \frac{1}{r^2} \frac{\partial}{\partial \phi} \left( \frac{1}{\rho_{th}} \frac{\partial T}{\partial \phi} \right) + \frac{\partial}{\partial z} \left( \frac{1}{\rho_{th}} \frac{\partial T}{\partial z} \right) = -w. \quad (D.1)$$

in which $T$ is the temperature, $\sigma_w$ is the thermal conductivity of the insulation, and $w$ is the power generated per unit volume. If we further state that $\partial T/\partial \phi$ and $\partial T/\partial z$ are zero and that the thermal resistance $\rho_{th}$ is a constant, this equation reduces to

$$\frac{1}{r} \frac{d}{dr} \left( r \frac{dT}{dr} \right) = -w \rho_{th}. \quad (D.2)$$

The power $w$ generated per unit volume equals

$$w = \frac{I_0^2}{(2\pi r)^2 \sigma}, \quad (D.3)$$

in which $\sigma$ stands for the electrical conductivity of the insulation.

If we enter equation (D.3) in equation (D.2) and integrate once, we find

$$r \frac{dT}{dr} = -\rho_{th} I_0^2 \int_{R_c}^r \frac{dr'}{4\pi^2 (r')^2 \sigma} + C, \quad (D.4)$$
in which \( C \) is an integration constant, which may be used to add the contribution of the conductor losses. As these are disregarded in this appendix, constant \( C \) is set to zero. Then equation (D.4) may be written as

\[
dT = -\rho_{th} I_0^2 \left( \frac{1}{r} \int_{r'=R_t}^{r} \frac{dr'}{4\pi^2 (r')^2 \sigma} \right) dr.
\]

(Integrating once more yields)

\[
T_r = -\rho_{th} I_0^2 \int_{R_t}^{r} \int_{r'=R_t}^{r'} \frac{dr''}{4\pi^2 (r'')^2 \sigma} dr' + C_1,
\]

in which \( C_1 \) is an integration constant. For \( r=R_t \), the integral expression becomes zero. In this case, \( T_r \) must equal the temperature of the conductor \( T_c \). Therefore, \( C_1 \) equals \( T_c \).

We thus arrive at the equation describing the temperature drop between conductor and insulation at radius \( r \) which is due to heating by the leakage current

\[
T_r - T_c = -\rho_{th} I_0^2 \int_{R_t}^{r} \int_{R_t}^{r'} \frac{dr''}{4\pi^2 (r'')^2 \sigma} dr'.
\]
APPENDIX

Calculation of DC-field and insulation resistance

In this appendix equations (2.6) and (2.10) will be derived. Equation (2.6) describes the stable DC-field during stage III, whereas equation (2.10) describes the insulation resistance of the insulation in a cable during stage III.

**DC-field**

Let \( R \) be the total insulation resistance per metre cable:

\[
R = \frac{1}{2\pi} \int_{R_i}^{R_o} \frac{\rho_r dr}{r}, \quad (E.1)
\]

in which \( \rho_r \) stands for the specific insulation resistance. The other symbols are explained in Figure (E.1).

The insulation resistance per metre cable from the conductor to radius \( r \) is given by

\[
R_r = \frac{1}{2\pi} \int_{R_i}^{r} \frac{\rho_{r'} dr'}{r'}. \quad (E.2)
\]

The voltage at radius \( r \) with reference to radius \( R_o \) (the lead-sheath) is given by

\[
U_r = \left(1 - \frac{R_r}{R}\right) U \quad (E.3)
\]

and the field strength at radius \( r \) is given by

\[
E_r = \frac{dU_r}{dr} = \frac{U}{R} \frac{dR_r}{dr}. \quad (E.4)
\]
Putting equations (E.1), (E.2) and (E.4) together ends up with

\[ E_r = U \frac{\rho_r}{R_o} \frac{r}{\int_{R_i}^{R_o} \frac{\rho_r}{r} dr}. \] (E.5)

The insulation resistance depends on temperature and field according to

\[ \rho_r = \rho_0 \exp(-\alpha T_r) \exp(-\gamma E_r), \] (E.6)

in which \( \rho_0 \) stands for the specific insulation resistance at 0°C and 0 kV/mm, \( \alpha \) is the temperature dependency coefficient, \( \gamma \) the field dependency coefficient and \( T_r \) is the temperature at radius \( r \).

We introduce factor \( k \) which is given by

\[ k = \frac{\alpha \Delta T}{\ln \frac{R_o}{R_i}}, \] (E.7)

in which \( \Delta T \) stands for the total temperature drop across the insulation.

We now may write

\[ T_r = \frac{k}{\alpha} \ln \left( \frac{R_o}{r} \right) + T_s, \] (E.8)

in which \( T_s \) stands for the temperature at radius \( R_o \) (the lead-sheath).

Using equations (E.5) and (E.8) it follows that

\[ E_r = U \frac{1}{R_o} \frac{r}{\int_{R_i}^{R_o} \frac{1}{r} \left[ -k \ln \left( \frac{R_o}{r} \right) \exp(-\gamma E_r) \exp(-\alpha T_s) \right] \exp(-\gamma E_r) \exp(-\alpha T_s) dr}. \] (E.9)

Recognizing that

\[ \exp\left[ -k \ln \left( \frac{R_o}{r} \right) \right] = \left( \frac{r}{R_o} \right)^k, \] (E.10)
it follows finally that

$$E_r = U \frac{r^{k-1} \exp(-\gamma E_r)}{\int_{R_i}^{R_o} r^{k-1} \exp(-\gamma E_r) dr},$$  \hspace{1cm} (E.11)$$

which is the equation as used in Chapter 2 (equation (2.6)).

**Insulation resistance**

The total insulation resistance per metre cable follows from equations (E.1) and (E.6):

$$R = \frac{1}{2\pi R_i} \int_{R_i}^{R_o} \frac{\rho_0 \exp(-\alpha T_s)}{r} \exp(-\gamma E_r) dr. \hspace{1cm} (E.12)$$

Using equation (E.7) this may be written as

$$R = \frac{1}{2\pi R_i} \int_{R_i}^{R_o} \rho_0 \exp\left(-k\ln\left(\frac{R_o}{r}\right)\right) \exp(-\gamma E_r) \exp(-\alpha T_s) dr. \hspace{1cm} (E.13)$$

Using equation (E.10) we arrive at

$$R = \frac{\exp(-\alpha T_s)}{2\pi} \int_{R_i}^{R_o} \rho_0 \left(\frac{r}{R_o}\right)^k \exp(-\gamma E_r) dr, \hspace{1cm} (E.14)$$

which can be further simplified to

$$R = \frac{\exp(-\alpha T_s)}{2\pi \sigma_0 R_i^k} \int_{R_i}^{R_o} r^{k-1} \exp(-\gamma E_r) dr, \hspace{1cm} (E.15)$$

in which it has been used that $\sigma_0 = 1/\rho_0$. This is the equation as used in Chapter 2 (equation (2.10)).
APPENDIX

Flow-diagram field-software

The field and charge distributions in stages II, III*, IV and VI are time- and temperature-dependent. They can be calculated by the aid of a computer using equations (2.3)-(2.5), as explained in Chapter 2. This appendix shows the flow-diagram of the computer program that calculates the distributions. The equations with reference to the cylindrical geometry of a cable.

The program starts with known, initial distributions of electric field, charge, temperature, conductivity and current density. Then, the time is increased by a step $dt$. After this, the distributions are determined using the equations as shown in Figure F.1. The temperature distributions is thought to be independent of the distributions of the electrical quantities$^{34}$. When all distributions are calculated, the time is increased again by a step $dt$ after which the whole process starts again. The program may be stopped when the quantities do not change significantly in time anymore. The cable has arrived a stable stage.

---

$^{34}$ Therefore, no time-dependent fields taking into account the insulation losses can be calculated with this software.
Start with initial distributions of:

\[ E(r, t) \] - el. field  \[ T(r, t) \] - temperature  
\[ \rho(r, t) \] - space charge  \[ J(r, t) \] - current  
\[ \sigma(r, t) \] - conductivity  

Increase time step: \( t = t + dt \)

Calculate new \( T(r, t) \)

Calculate new \( \rho(r, t) \):
\[ \nabla \cdot J + \partial \rho / \partial t = 0 \]

Calculate new \( E(r,t) \):
\[ \nabla \cdot \varepsilon E = \rho \]
\[ \int E \, dt = U \]

Calculate new \( \sigma(r, t) \):
\[ \sigma = \sigma_0 \exp(\alpha T) \exp(\gamma E) \]

Calculate new \( j(r,t) \):
\[ J = \sigma E \]

Figure F.1 The flow-diagram of the computer program that calculates time- and temperature dependent fields.
List of symbols

\begin{itemize}
  \item \(a\) capacitance of "healthy" part of object
  \item \(b\) capacitance of rest-insulation in series void; width of potential energy barrier; parameter equal to \(v\Delta T\) regarding the pulsed electro-acoustic method (equation (4.18), Appendix A)
  \item \(c\) capacitance of void
  \item \(d\) thickness of sample
  \item \(d_{33}\) piezo strain constant
  \item \(D_r\) void distribution at radius \(r\)
  \item \(E\) electric field intensity
  \item \(E_{AC}\) electric field intensity for AC
  \item \(E_c\) electric field intensity at the conductor
  \item \(E_{DC}\) electric field intensity for DC
  \item \(E^{MAX}\) maximum electric field intensity in a sample regarding a space charge test
  \item \(E_p\) electric field intensity for impulses superimposed on DC voltage
  \item \(f\) field enhancement factor
  \item \(G\) air impermeability; acoustic generation coefficient
  \item \(h\) response function in time-domain
\end{itemize}
### List of symbols

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H$</td>
<td>potential energy barrier in the ionic conduction model; response function in frequency-domain</td>
</tr>
<tr>
<td>$H_s$</td>
<td>energy barrier according to Schottky</td>
</tr>
<tr>
<td>$I$</td>
<td>load current</td>
</tr>
<tr>
<td>$I_0$</td>
<td>leakage current per metre cable</td>
</tr>
<tr>
<td>$J$</td>
<td>current density</td>
</tr>
<tr>
<td>$J_0$</td>
<td>Schottky constant</td>
</tr>
<tr>
<td>$k$</td>
<td>parameter (introduced in equation (2.7), §2.2)</td>
</tr>
<tr>
<td>$L$</td>
<td>distance between successive energy barriers; lifetime</td>
</tr>
<tr>
<td>$l_p$</td>
<td>mean length of a paper pore</td>
</tr>
<tr>
<td>$n$</td>
<td>discharge repetition rate</td>
</tr>
<tr>
<td>$N_0$</td>
<td>concentration of charged particles</td>
</tr>
<tr>
<td>$p$</td>
<td>probability per unit time for a particle to cross a barrier; pressure</td>
</tr>
<tr>
<td>$P$</td>
<td>transmission power</td>
</tr>
<tr>
<td>$q$</td>
<td>charge of a particle; discharge magnitude</td>
</tr>
<tr>
<td>$Q$</td>
<td>integrated discharges as a quality number</td>
</tr>
<tr>
<td>$Q_s$</td>
<td>total space charge in the insulation per metre cable</td>
</tr>
<tr>
<td>$q_{det}$</td>
<td>minimum detectable discharge magnitude</td>
</tr>
<tr>
<td>$r$</td>
<td>radius</td>
</tr>
<tr>
<td>$R$</td>
<td>relative rate of recombination as a percentage of the carrier concentration; acoustic reflection coefficient</td>
</tr>
<tr>
<td>$r_0$</td>
<td>offset rate of recombination</td>
</tr>
<tr>
<td>$R_a$</td>
<td>resistance of &quot;healthy&quot; part of object</td>
</tr>
<tr>
<td>$R_b$</td>
<td>resistance of rest-insulation in series with void</td>
</tr>
<tr>
<td>$R_c$</td>
<td>resistance of void</td>
</tr>
</tbody>
</table>
\( r_i \)  rate of recombination

\( R_i \)  inner radius of the insulation

\( R_o \)  outer radius of the insulation

\( R_{total} \)  total insulation resistance per metre cable

\( S \)  standard deviation

\( t \)  time

\( \Delta t \)  time between discharges

\( T \)  temperature; acoustic transmission coefficient

\( \Delta T \)  temperature drop across the insulation; pulse width regarding the pulsed electro-acoustic method

\( t_{63\%} \)  time in which the magnitude of the electric field at a certain point in the insulation has changed for 63\%

\( T_{amb} \)  ambient temperature

\( T_c \)  temperature of the conductor

\( t_L \)  statistical time lag

\( t_R \)  recovery time

\( T_r \)  temperature of the insulation at radius \( r \)

\( T_s \)  temperature of the lead-sheath

\( U \)  voltage across cable

\( \Delta U \)  voltage drop during which no discharges occur; voltage step during breakdown test

\( U_0 \)  nominal voltage of cable

\( U_c \)  voltage across a void

\( U_{DC} \)  DC voltage as used in the pulsed electro-acoustic method

\( U_{iac} \)  inception voltage

\( U_{min} \)  minimum breakdown voltage
List of symbols

\( U_p \) pulsed voltage as used during the pulsed electro-acoustic method
\( U_r \) residual voltage
\( U_s \) asymptotic voltage across void if it would not discharge
\( v \) speed of sound
\( v_d \) drift velocity of particles
\( v_s \) electric measurement signal regarding the pulsed electro-acoustic method
\( v_{s, \text{decon}} \) deconvoluted version of \( v_s \)
\( w \) heat power generated per unit volume
\( W_c \) heat power per metre cable generated by the heat losses in the conductor
\( W_p \) heat power per metre cable generated by the insulation losses
\( x \) location
\( Z \) acoustic impedance
\( \alpha \) temperature dependency coefficient of the conductivity
\( \beta \) shape factor of the potential energy barrier
\( \beta_s \) Schottky constant
\( \gamma \) electric field dependency coefficient of the conductivity
\( \varepsilon \) permittivity
\( \varepsilon_0 \) permittivity of air
\( \varepsilon_r \) relative permittivity
\( \eta \) viscosity
\( \kappa_s \) surface charge density
\( \mu \) mobility of particles
\( \rho \) space charge density
\( \rho_{\text{sh}} \) specific thermal resistivity
$\sigma$  specific conductivity

$\sigma_0$  specific electric conductivity at 0°C and 0 kV/mm

$\sigma_{1, 2}$  surface charges at the electrodes of the pulsed electro-acoustic method

$\tau$  time constant

$\omega_0$  attempt-to-escape frequency
References


IEC 554-2, "Specification for cellulosic paper for electrical purposes".


References


[22] CIGRE Working Group 02 of Study Committee No. 21, "Recommendations for Tests of Power Transmission DC Cables for a Rated Voltage up to 600 kV", Electra No 72, pp. 105-114, 1980.


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[83] Personal conversation with G. Clasen.

[84] Personal conversation, CIGRE Working Group 02, Study Committee 21.


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Acknowledgements
Samenvatting
LADINGEN EN ONTLADINGEN IN HOGE GELIJKSPANNINGSKABELS

Hoge gelijkspanningskabels (HVDC-kabels) van het massa-geïmpregneerde type zijn op zijn minst even betrouwbaar gebleken als hoge wisselspanningskabels. Ondanks dit gegeven, zijn er nog vragen, betreffende het technisch functioneren van de HVDC kabel, onbeantwoord gebleven. Tevens zijn de aanbevolen elektrische beproevingen van de HVDC kabel onderontwikkeld vergeleken met die voor wisselspanningskabels. Het doel van deze studie is tweeledig. In de eerste plaats wil dit werk de kennis van de HVDC kabel vergroten. In de tweede plaats doet het werk een voorstel voor beter onderbouwde testregels voor HVDC kabels. De zo vergaarde kennis en beproevingsvoorschriften zijn met name interessant voor de nieuwe generatie HVDC kabels met hogere spanningen en hogere transportvermogens.

In hoofdstuk 1 wordt een korte inleiding over hoge gelijkspanningskabels gegeven.

Hoofdstuk 2 beschrijft de elektrische veld- en ladingsverdelingen in de isolatie van een gelijkspanningskabel gedurende verschillende spanningsstadia. De veldberekeningen onder gelijkspanning zijn complexer dan de berekeningen onder wisselspanning. De veldverdeling onder gelijkspanning is afhankelijk van geometrie, spanning, geleiding, temperatuur, ruimtelading en tijd. Om de veldverdelingen in ieder willekeurig stadium te berekenen, is een computerprogramma geschreven.

Ten aanzien van de elektrische veldsterkte blijkt een polariteitsomkering voor een kabel in een koude omgeving gevaarlijker te zijn vergeleken met dezelfde beproeving voor een kabel in een warme omgeving.

De lekstroom van een gelijkspanningskabel in een voldoend warme omgeving speelt een belangrijke rol in de veldverdeling. Het opwarmen van de kabel door de lekstroom kan zelfs tot een thermische doorslag leiden. Dit gegeven is van belang bij het beproeven van oliedrukkabels bij hoge temperaturen en bij het ontwikkelen van nieuwe isolatiematerialen voor gelijkspanning.

In hoofdstuk 3 wordt de hoge gelijkspanningskabel van het massa-geïmpregneerde type besproken in relatie tot deelontladingen. Het blijkt mogelijk te zijn enkele fysische gedragingen van de kabel te relateren aan de gemeten ontladingspatronen. Plotseling druveranderingen in de kabel alsmede het toenemen van het aantal holtes tijdens de afkoel fase leveren karakteristieke ontladingspatronen op. In dit werk zijn tevens resultaten van ontladingsmetingen vlak voor doorslag opgenomen.
Hoofdstuk 4 vertelt de bevindingen van ruimteladingsmetingen aan geïmpregneerd papier. Verrassend genoeg blijken de verdelingen van ruimtelading in hoge mate reproduceerbaar. Dit in tegenstelling tot de ladingsspatronen in plastics; hier zijn de patronen vaak erg afhankelijk van het materiaaltype en soms zelfs van de batch.

Lading wordt geïnjecteerd in het papier dat aan een electrode ligt. De verdeling van de ruimtelading is altijd van het "homocharge" type. Het aangroeien en afvloeien van de ruimtelading verloopt volgens specifieke patronen. Dit aangroeien en afvloeien in de tijd kan grofweg met twee tijdconstanten beschreven worden. De waarnemingen zijn in hoge mate onafhankelijk van het elektrodemateriaal, -polariteit en de aangelegde spanning.

Het gevolg van de "homocharge" verdeling is een veldverhoging in het papier. De laagste veldverhogingen blijken op te treden in dunne papiersoorten met een hoge luchtondoorlaatbaarheid en isolerende olieën met een relatief lage elektrische weerstand.

Indien meerdere papierlagen op elkaar gestapeld worden, migreert de ruimtelading niet van laag naar laag. De geïnjecteerde ruimtelading blijft dan ook beperkt tot de eerste papierlaag naast een electrode. Bij de produktie van HVDC kabels verdient het dan ook aandacht om dunne, hoog luchtondoorlaatbare papiersoorten aan te brengen naast de geleider en loodmantel.

Hoofdstuk 5 beschrijft een physisch model dat de waarnemingen betreffende ruimtelading goed voorspelt. De geleiding in geïmpregneerd papier is hoogstwaarschijnlijk van het ionische type. Op een elektrode-papier overgang vindt waarschijnlijk Schottky injectie plaats. Het model gebruikt genoemde geleidings- en injectiemechanismen en combineert dit met de plaatsafhankelijke recombinaat van ladingsdragers. De modelparameters kunnen over een breed gebied gevarieerd worden zonder dat de modelresultaten noemenswaardig afwijken van de waarnemingen.

In hoofdstuk 6 wordt een voorstel gedaan voor nieuwe beproevingsregels voor HVDC papierkabels. Als startpunt zijn de huidige CIGRE aanbevelingen gebruikt. Deze worden uitgebreid met de ervaringen die in dit werk zijn opgedaan.

De kennis van de elektrische levenslijn van hoge gelijkspanningskabels is niet compleet. Ten aanzien van het ontwikkelen en testen van nieuwe generatie HVDC kabels is het daarom nodig diagnostische proeven toe te voegen aan de bestaande aanbevelingen. Deelondladingen- en dielektrische proeven zijn goede kandidaten voor een diagnostische proef. Wat betreft een deelondladingstest worden het \( q-n \) diagram en het kwaliteitsgetal \( Q \) voorgesteld als mogelijke criteria om "goede" van "slchte" kabels te onderscheiden.

De omgevingstemperatuur waarbij hoge gelijkspanningskabels en -garnituren getest worden, dient in overeenstemming te zijn met de omgevingstemperatuur die in de praktijk ervaren zal worden.

Fabrieksmonoren dienen op dezelfde wijze beproefd te worden als kabels.

M.J.P. JEROENSE
Zusammenfassung:

LADUNGEN UND ENTLADUNGEN IN ENERGIEKABELN FÜR HOHE Gleichspannungen


Im ersten Kapitel wird eine kurze Einführung über Kabel, Teilentladungen, Raumladungen und Prüfmethoden bei hohen Gleichspannungen gegeben.


Die Polaritätsumkehr bei niedrigen Umgebungstemperaturen ist ein härterer Test für ein Gleichspannungskabel als bei entsprechend hohen.

Ist die Kabeltemperatur hinreichend hoch, wird das elektrische Feld so stark vom Leckstrom beeinflußt, daß dies letztendlich zu einem Wärmedurchschlag führen kann. Beachtenswert ist diese Erkenntnis vor allem für Öldruckkabel und die Entwicklung von neuen Isolierstoffen für Gleichspannungskabel.

In Kapitel 3 wird das Teilentladungsverhalten von Massekabeln für hohe Gleichspannungen
Zusammenfassung

untersucht. Entsprechende charakteristische Teilentladungsmuster können durch das Verständnis der Vorgänge im Kabel begründet werden. So wird das Teilentladungsmuster nach Abschalten der Last durch Druckänderungen im Kabel und die darauf zurückgehende Zunahme der Hohlräume durch Kontraktion der Öl-Papier-Isolierung verursacht.

Kapitel 4 behandelt das Raumladungsverhalten in Massekabeln, das sich als gut reproduzierbar erwies. Dies steht im Gegensatz zu Ergebnissen an Isolierstoffen aus Elastomeren, die sehr stark von der Materialqualität, d.h. von Hersteller und sogar von der jeweiligen Produktionscharge eines Herstellers, sowie den Eigenschaften der Grenzfläche zwischen Elektroden und Dielektrika abhängig sind.

Berührt eine Papierlage eine Elektrode, werden Ladungen in das imprägnierte Papier injiziert. Die resultierende Raumladungsverteilung ist allzeit vom homocharge-Typ, deren Aufbau und Zerfall charakteristisch verläuft und daher mittels zweier Zeitkonstanten beschrieben werden kann. Diese Vorgänge sind in einem weiten Bereich unabhängig vom Elektrodentyp, -polarität und angelegter Spannung.

Die homocharge Raumladung bewirkt eine Verstärkung des elektrischen Feldes in der jeweiligen Papierlage. Um diese Felderhöhung in Massekabeln für hohe Gleichspannungen möglichst gering zu halten, sollten dünne, undurchlässige Papiere und Isolieröle mit geringem Widerstand für deren Konstruktion verwendet werden.


Kapitel 6 enthält Vorschläge zu weiterentwickelten Tests an Massekabeln für hohe Gleichspannungen. Die vorgeschlagenen Prüfungen basieren auf den CIGRE Test Empfehlungen, sind jedoch erweitert um Methoden, die in dieser Arbeit gewonnene Wissen berücksichtigen.

Die Kenntnis der die Lebensdauerkurve bestimmenden Parameter für Gleichspannungskabel ist unvollständig. Deshalb ist für neue Generationen von Gleichspannungskabeln die Erweiterung der bestehenden Tests um eine Zustandsdiagnose anzuraten. Hilfreich erscheinen hierbei Teilentladungs- und Isolations(Polarisations)strommessungen zu sein. Als Prüfmethoden hinsichtlich von Teilentladungsmessungen können das...
Teilentladungsamplituden-Teilentladungsanzahl-Diagramm als auch die Summenladung innerhalb einer bestimmten Meßzeit herangezogen werden.

Kabel und deren Armaturen sollten bei Umgebungstemperaturen geprüft werden, die die realen Betriebsbedingungen widerspiegeln.

Fabrikgefertigte Kabelmuffen werden am besten so getestet wie das Kabel.

M.J.P. Jeroense
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