STELLINGEN

behorende bij het proefschrift van

Edward Gulski

1. In de toekomst zal de grootte van ontladingen in pico-coulombs als kern van ontladingsmetingen met grote waarschijnlijkheid worden aangevuld met een aantal abstracte grootheden zoals beschreven in dit proefschrift.

2. Automatisering van routinematische ontladingsmetingen maakt het mogelijk een wereld-wijde databank op te bouwen voor de diagnostiek van hoogspanningscomponenten in de elektrische energietechniek.

3. De reputatie van wetenschappers wordt - in tegenstelling tot die van veel andere beroepsgroepen - bepaald door vaak anonieme beoordelaars, andere wetenschappers. Belangrijk bij het verwerven van eigenwaarde op zijn of haar gebied is dat het werk van een wetenschapper door andere wetenschappers als nuttig, vindingrijk en zelfs vernieuwend wordt beoordeeld.

4. Niet alleen uit beleefdheid, maar voornamelijk uit erkenning dat het proces van ontdekking continu is, zou iedere respectabele wetenschappelijke publicatie moeten beginnen met een verslag dat vermeld waar de oorsprong ligt van de nieuwe ideeën die in deze publicatie worden ontvouwd.

5. Wanneer met het opheffen van de Europese grenzen geen uniforme normen op het gebied van milieu worden ingevoerd bij alle lidstaten, wordt het al bestaande spanningsveld tussen milieu en economie sterk vergroot.

6. De groei van de economie is het meest opvallend daar, waar de meeste vrijheid heerst.

7. Naast technologische vooruitgang zijn vooral ook politieke beslissingen bepalend voor het moment waarop de elektrische auto een reële kans krijgt op de afzetmarkt.

8. Het mooie van Nederland is dat niemand extremistische groeperingen hoeft te verbieden, want deze krijgen toch maar een minime steun van de bevolking.

9. Coca-Cola is als geen ander merk een sublimering van de democratie.

10. De meeste klachten over moeilijkheden bij het gebruik van een belastingsgids ontstaan door de dikte van de gids. Deze klachten zouden in de meeste gevallen verdwijnen wanneer men zich zou realiseren dat de belastingsgids net als een telefoonboek systematisch is opgebouwd.
COMPUTER-AIDED RECOGNITION
OF PARTIAL DISCHARGES
USING STATISTICAL TOOLS
COMPUTER-AIDED RECOGNITION
OF PARTIAL DISCHARGES
USING STATISTICAL TOOLS

PROEFSCHRIFT

Te verkrijging van de graad van doctor aan de
Technische Universiteit Delft op gezag van de
Rector Magnificus, prof. drs. P.A. Schenck, in het
openbaar te verdedigen ten overstaan van een
commissie door het College van Dekanen
daartoe aangewezen, op maandag
14 oktober 1991, te 14.00 uur.

Door

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elektrotechnisch ingenieur
geboren te Włocławek

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Aan Piet
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Summary

Discharge detection is important for the evaluation of insulating constructions and in recognizing defects in these constructions. The conventional method of oscillographic observation provides only a limited recognition of defects which cause discharges. The trend towards the automatization of detection and recognition in tests of cables, transformers and other insulated devices is evident: one of the undoubted advantages of a computer-aided measuring system is the ability to process a large amount of information and transform this information into an understandable output.

In this thesis the improvement of the recognition of discharges by means of computer-aided measurements is studied.

In chapter 1 a general introduction is given.

In chapter 2 the specification for a computer-aided analysis is discussed. In section 2.1 an analysis of a number of discharge quantities is proposed. For a partial discharge analyzer based on conventional detection methods, (bandwidth about 400 kHz) relevant design choices have been made in section 2.2.

In chapter 3 the configuration of a computer-aided discharge analyzer is presented. A continuous and multi-parameter registration is realized.

In chapters 4, 5, 6 and 7 physical models of discharge sources in gases, liquids and solid materials have been tested with this analyzer. The tests show that significant differences can be found in the behaviour of different discharge quantities. Not only the basic quantities such as discharge magnitude, inception voltage, the number of discharges and the phase position, but also the deduced quantities such as pulse count and mean pulse height phase distributions were taken into account. An important step is to analyze these registered data with statistical operators like skewness, kurtosis, cross-correlation factor, etc.
In chapter 8 the development a systematic method for the recognition of defects using the statistical operators is reported.

In chapter 9 the application of the above method to actual technical objects is discussed. The data obtained from tests using the physical models are used in a simple algorithm called the recognition rate. The origin of discharges in actual technical objects could be traced back in this way.
Chapter 1
Introduction

1.1 General aspects

An electricity supply system is characterized by an extensive source-to-user network which functions as an indispensable link between the sources of energy and and the large number of users. The functions of this network in the Netherlands are divided into three main categories [1]:

- the coupling of production centers at 220kV or 380kV level
- transmission, in the voltage ranges of 50kV, 110kV or 150kV
- medium voltage distribution, from 10kV to 25kV.

Further there exists an extensive low-voltage network.

The equipment in all these systems, the transformers, the cables and the circuit-breakers have to be insulated for these high-voltages. Over the years a choice has been made among different insulating materials (oil, paper, \(SF_6\), epoxy resin, rubber, \(PE\), \(XLPE\)). Unfortunately, these materials cannot be processed without the introduction of defects and can therefore not be stressed at their theoretical maximum electric-field strength [2]. The intrinsic breakdown strength of \(PE\) is about 700kV/mm [3], whereas in practice cables are designed at field strengths of 5-10kV/mm only [4,5]. Thus the technical constructions are used at a low percentage level of the theoretical maximum electrical strength of the material. This discrepancy is due to microscopic imperfections and defects in the materials.
CHAPTER 1. INTRODUCTION

Generally these defects consists of many kinds of gas- and oil-filled micro cavities, sharp points on the conductors, metal splinters, inclusions of dirt, fibres and other foreign particles [6,7]. They may cause local field concentration, so that in the vicinity of the defect the breakdown strength is reached. The effect of these defects depends on their geometry and their dimensions; the danger of smaller defects increases with higher values of electrical strength [8,9]. These inhomogeneities often result in partial discharges. These discharges injure the dielectric material and may cause failure in high-voltage insulating systems; through the years, partial discharge measurement has become an indispensable tool in the quality control of electrical insulation [10]. Many successful methods for detection, location and evaluation of partial discharge phenomena have been developed [8]. However, the correlation found between the measured discharge magnitude and the discharge process that takes place inside the insulation is limited [11].

Through the years, many discharge quantities were introduced in order to improve this situation [12]. Although the quantities used today do not predict the lifetime of the dielectric, they do give information on its quality. Partial discharges measurement often provides a means for detecting defects that would otherwise lead to the breakdown of the dielectric [8].

Further, the international trend in the development of electrical equipment is towards the increasing the transmission capacity and also towards the reduction of the insulation volume [13,14]. This trend is leading to higher field strengths so that the danger of smaller defects will be evident. As each defect has its own particular degradation mechanism it is important to know the correlation between discharge patterns and the kind of defect. Therefore progress in the recognition of discharge patterns and their correlation with the kind of defect is becoming increasingly important in the quality control of insulating constructions [15].

1.2 State of the art

There are four types of partial discharges:
1. Corona discharges (figure 1.1a) occur at sharp points protruding from electrodes in gases and in liquids. In air these discharges are not dangerous unless decomposition products like ozone or nitrites injure the neighboring insulation. Corona discharges in sulphur hexafluoride gas ($SF_6$) are dangerous, due to aggressive and poisonous decomposition products of $SF_6$, which are detrimental to dielectric surfaces [8,16]. Corona discharges under oil may cause a decrease in the breakdown stress due to pollution by small conductive particles.

![Diagram of insulation defects and their stylized discharge patterns](image)

**Figure 1.1:** Typical insulation defects and their stylized discharge patterns.

a) corona discharges  
b) surface discharges  
c) cavity discharges  
d) treeing discharges

2. Surface discharges (figure 1.1b) may occur in gases or in oil if there is a strong stress component parallel to the dielectric
surface. These discharges are known to cause deterioration of
dielectrics by heating the dielectric boundary, through charges
trapped in the surface and through the formation of chemicals
such as nitric acid and ozone. These may cause depolymeriza-
tion, stress cracking, gassing, etc. leading to the erosion of the
dielectric surface [8].

3. Internal discharges (figure 1.1c) are in many cases the most im-
portant cause of the reduction of voltage life. These discharges
occur in gas-filled cavities, but oil-filled cavities can also break
down and cause gaseous discharges afterwards. Dependent on
the field strength, the kind of material and the discharge mag-
nitude, internal discharges are capable of degrading the insu-
lation [17]. This degradation starts with material erosion on
the inner surface of a cavity. Pit formation, field concentration
and tree formation may lead to final dielectric failure [18].

4. Electric trees (figure 1.1d) can start from conducting particles
or from a cavity in solid insulation. After treeing has started
a hollow stem and several branches are generated. The time
which elapses prior to the manifestation of a tree depends on
the applied voltage and can take hours, weeks or even years.
Considerable discharges may occur in hollow spaces and these
constitute a special cases of internal discharges. The growth
of trees is in many cases destructive and breakdown may take
place in a far shorter period than that which elapses prior to
manifestation [19,20].

For a better understanding of the discharge process and discharge
measurement, different electrical models were developed to describe
the combination of defect and dielectric [21,22,23,24,25]. The most
popular description of the recurrence of partial discharges at a.c.
voltage is given by the capacitance model (abc-model) of the dielectric-
defect combination [22,26]. By means of this equivalent the mag-
nitude of the discharge-transfer and of the energy-transfer can be
estimated (figure 1.2).
Various methods for partial discharge detection and measurement
were developed and applied to cables, transformers, capacitors, ma-
1.2. STATE OF THE ART

![Diagram of capacitance equivalent of a dielectric circuit.](image)

**Figure 1.2:** Capacitance equivalent of a dielectric circuit.

The most frequently used method is electric pulse detection [16,30, 31]. This method is based on the measuring of the current impulses caused by a discharge in the defect and which occur in the circuit in series with the dielectric. In electric pulse detection two types of detection impedances, $RC$ or $RLC$, are generally used across which, voltage impulses are caused by the current impulses in the sample. Starting from this principle, two different discharge-detecting methods can be distinguished. The first is called the straight method and is based on the amplification of the voltage signals across a detection impedance [30,31] (figure 1.3a).

The second is called the bridge method or balanced method (figure 1.3b). Using this method, discharges in the sample are detected as described above, but discharge pulses from outside the sample can be suppressed. This elimination of external interference is realized by means of two impedance arms $Z_m$ and $Z'_m$ which can be varied to balance the bridge [26,29].

All detection methods focus on three main aims:

1. To determine the presence of partial discharges and to estimate their magnitude.

2. To locate the site of the discharges.

3. To estimate the danger caused by the detected discharges. Above all, information on the type of defect is important [16, 27,32].
Figure 1.3: Detection circuits for partial discharges.

a) straight detection

b) balanced detection

HV - high voltage;
Ck - coupling capacitance;
Zm/m' - detection impedance;
D - discharge detector;
a - test object; a' - dummy object
1.2. STATE OF THE ART

It is known that the characteristics of discharges may change substantially during service and that the occurrence of discharges depends on the temperature, pressure, applied voltage and the test duration. The occurrence of discharges may cause structural changes in the defects so that the discharge patterns may be subject to change [25,32,33,34,35,36]. Oscillograms give valuable information about the type and origin of discharges; moreover diagrams of discharge magnitude as a function of voltage also help to determinate the cause of discharges [8,16]. The changes in the behaviour of discharge magnitude and extinction voltage may add to these findings. However, the combination of these characteristics gives an indication only, much depends on its intelligent use and room is left for considerable doubt.

In recent years, investigation into the use of digital techniques for the evaluation of partial discharges has been becoming increasingly important. The trend towards automation in tests for cables, transformers and other insulated devices is evident [11,37,38,39,40].
One of the undoubted advantages of a computer-aided measuring system is the ability to process a large amount of information and to transform this information into an understandable output. Many computer aided systems have been developed for the measurement and understanding of partial discharge phenomena. Through the years attention has been paid to two main trends.
The first trend concentrates on the improvement of the sensitivity, bandwidth, or impulse response of measurements systems. This improvement has led to somewhat better noise reduction, partial discharge site location and a better understanding of the physical mechanisms of discharges [40,41,42,43,44].
The second trend is in the direction of the improvement of the recognition of discharge sources and the evaluation of measuring results, which result in analyzing systems which will assist in the judgment of the quality and the condition of insulating systems [45,46,47,48,49].
The work of this thesis belongs to this second category.
1.3 Object of the present study

The object of this study is to improve the recognition of discharges by computer-aided measurements of partial discharges. Conventional methods of oscillographic observation provide a limited recognition of the defects causing discharges and another approach would be welcome. The approach of this study is therefore based on the following two main facts:

1. A powerful interpretation of discharge signals can be achieved when a large number of discharge quantities are measured simultaneously, making use of their time behaviour.

2. The ability of a computer-aided system to process a large quantity of measuring data, within a short test period makes it very useful for this purpose.

The efficiency of a computer-aided system will be analyzed with regard to the recognition of different discharge defects, of the type as shown in figure 1.4. A system will be developed with the following aims:

1. Recognition of different kinds of defects in insulating systems.

2. Observation of changes in these defects under the influence of partial discharges.
### 1.3. OBJECT OF THE PRESENT STUDY

<table>
<thead>
<tr>
<th>Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Corona discharges</td>
<td>Air, oil</td>
</tr>
<tr>
<td>Surface discharges</td>
<td>Air, SF6, oil</td>
</tr>
<tr>
<td>Internal cavity discharges</td>
<td>Square cavity, flat cavity, narrow cavity, electrode bounded cavity, multiple cavities</td>
</tr>
<tr>
<td>Treeing discharges</td>
<td>Initiated by a sharp electrode, initiated by a cavity</td>
</tr>
</tbody>
</table>

**Figure 1.4:** Typical insulation defects.
Chapter 2
Automized analysis of discharges

2.1 Partial discharge quantities

Electrical discharges that do not completely bridge the distance between two electrodes are called partial discharges. They cause patterns of current impulses in the leads of a sample. If the voltage $V_c$ (figure 2.1) across the defect reaches the breakdown voltage $U^+$, a discharge occurs in the defect [8]. The voltage then drops to $V^+$ where the discharge extinguishes. This voltage drop takes place in less than 100ns [50,51]. After the discharge has been extinguished the voltage $V_c$ over the defect increases again. When voltage $V_c$ reaches $U^+$, a new discharges occurs. This happens several times, after which the high voltage-$V_a$ over the sample decreases and the high-voltage $V_c$ drops to $U^-$ where a new discharge occurs. In this way, groups of recurrent discharges which occur during the positive half and the negative half of the voltage cycle will be found. If a sample has several fault locations, more discharges will occur within intervals of a few $\mu$s or less.

To describe the characteristics of a discharge, many discharge quantities have been introduced over the years [12]. With regard to the observation time, these quantities can be divided into three main groups:

1. Basic quantities: quantities observed during one single voltage cycle.

2. Deduced quantities: integrated values of basic quantities observed throughout several voltage cycles, e.g. more than 100
cycles.


These three categories will be discussed here.

**BASIC QUANTITIES**
Quantities of the first group will be termed basic quantities and for their registration the momentary values of the test voltage and the discharge signal are registered.

It is known that the electrical activity of partial discharges can be represented by two independent quantities only:

1. **Discharge magnitude** - the apparent charge, see below.

2. **Discharge timing** - the position of the discharge instant related to the voltage cycle of the test voltage $V_a$.

- The amount of charge which is displaced by the discharge current $i_q(t)$ in the leads of the sample is referred to as the apparent charge $q_t$. This quantity is defined as:

$$q_t = b \cdot \Delta V$$  \hspace{1cm} (2.1)

where $b$ is the capacitance in series with the defect and $\Delta V$ the voltage drop across the defect (figure 1.2) [26]. The apparent charge is not equal to the amount of charge involved at the site of the discharge, which cannot directly be measured. The apparent charge is expressed in picocoulomb [10].
2.1. PARTIAL DISCHARGE QUANTITIES

- The position of the discharge (figure 2.2a) related to the phase of the test voltage cycle $V_a$ is described by the phase angle $\varphi_i$, whereas the momentary value of the test voltage $V_a$ during the occurrence of a discharge is represented by the ignition voltage $U_i$ [32,33,52,54].

![Diagram of basic partial discharge quantities.](image)

Figure 2.2: Diagram of basic partial discharge quantities.

These three quantities, the apparent charge $q_i$, the ignition voltage $U_i$, and the phase angle $\varphi_i$ are the only ones that describe the recurrence of partial discharges. Consequently all other basic quantities presented in this chapter are determined on the basis of these three.

- The energy that is supplied from outside is estimated by multiplying the apparent charge $q_i$ by the momentary value of the test voltage $U_i$ (figure 2.2d) [22,56,60]:

$$ p_i = q_i \cdot U_i $$

(2.2)
CHAPTER 2. AUTOMIZED ANALYSIS OF DISCHARGES

These external energy pulses can either be positive or negative, depending on the polarities of \( q_i \) and \( U_i \). This would mean that energy would be consumed in the defect as well as supplied to the source. However, the internal energy at the discharge which is responsible for damage of the dielectric will certainly be dissipated by every pulse. If all the external energy pulses are added algebraically over a long period, the ensuing net energy drawn from the source equals the energy lost by discharges in the defect [22,55].

- Quantity related to the deterioration of the dielectric is the energy dissipated by a discharge. This quantity is defined as:

\[
\Delta p_i \approx 0.7 \cdot q_i \cdot V_i
\]

(2.3)

where \( q_i \) equals the apparent charge and \( V_i \) is the inception voltage at which the sample starts to discharge and \( V_i \) is expressed in volts r.m.s. [26].

If the observation time is extended to the duration of one half cycle of the test voltage and more discharges occur, integrated quantities for the positive half and the negative half of the voltage cycle can be calculated.

- The voltage at the sample at which discharge pattern in a half cycle of the test voltage starts is called the momentary inception voltage \( U_{inc} \) (this quantity will be called further in this thesis: the inception voltage), and that at which the discharge pattern in a half cycle of the test voltage terminates is called the terminating voltage \( U_{term} \) (figure 2.2a) [10,36,53,57].

- Further the observation of single values of \( q_i \) and \( p_i \) during a half voltage cycle provides the following integrated values [56,58]:
  - the number of discharges: \( N_q \) (figure 2.2b)
  - the mean discharge magnitude: \( q_{mean} \) (figure 2.2c)
  - the maximum discharge magnitude: \( q_{max} \) (figure 2.2c)
2.1. PARTIAL DISCHARGE QUANTITIES

- the mean discharge energy: $p_{\text{mean}}$ (figure 2.2d)
- the maximum discharge energy: $p_{\text{max}}$ (figure 2.2d)
- the integrated discharge magnitude: $Q_s=\Sigma q_i$ (figure 2.2e)
- the integrated discharge energy magnitude: $W_s=\Sigma p_i$ (figure 2.2f).

The main aim for using the basic discharge quantities is the demand for an exact description of the discharge process during one voltage cycle. Three independent quantities are important for the description of this process, and are relevant to the degradation of the insulation:

1. The discharge magnitude $q_i$ can be related to the size of the discharge site and is also a reasonably good measure for the discharge energy at the discharge site, which may causes the detoriation of the dielectric [8,32].

2. The phase angle $\varphi_i$ (or the ignition voltage $U_i$) in combination with the electric field provides the information about the ignition conditions in the defect [10,20,52,59].

3. The number $N_q$ of discharges is related to ratio of the applied test voltage and the inception voltage [33,63]. The degradation of a dielectric is not dependent on discharge magnitude only, but also on the repetition rate of partial discharges [9,10,20,63].

DEDUCED QUANTITIES

Quantities of the second group will be termed deduced quantities. For their registration the basic quantities have to be observed during a time span that is much longer than the duration of one voltage cycle, e.g. more than 100 cycles. These quantities can be analyzed as a function of time and as a function of the phase angle. The quantities as function of time describe the changes of the basic quantities in the course of time. Two groups of quantities can be distinguished here.
1. The first group consists of quantities processed during the test time $T_T$; either for the positive half or the negative half of the voltage cycle as follows:
   \begin{itemize}
   \item the maximum discharge magnitude $q_{max}(t)$
   \item the mean discharge magnitude $q_{mean}(t)$
   \item the integrated discharge magnitude $Q_s(t)$
   \item the maximum discharge energy magnitude $p_{max}(t)$
   \item the mean discharge energy magnitude $p_{mean}(t)$
   \item the integrated discharge energy magnitude $W_s(t)$
   \item the inception voltage $U_{inc}(t)$
   \item the terminating voltage $U_{term}(t)$
   \item the number of discharges $N_q(t)$.
   \end{itemize}

2. The second group consists of the intensity spectra of the $q_i$- or $p_i$- magnitudes. During the measurement time $T_T$ the magnitudes were processed into distribution functions $H(q)$ or $H(p)$. In this way the number of pulses as a function of $q_i$- or $p_i$- magnitudes can be shown. This contains more information than the first group [41,64,55,60].

The quantities as function of the phase angle represent the recurrence of partial discharges related to their phase angle. The voltage cycle is divided into phase windows representing the phase angle axis (0-360°) (figure 2.3). If the observation takes place for several voltage cycles, four quantities can be determined in each phase window:

1. the sum of the discharge magnitudes observed in one phase window (discharge amount):
   \begin{equation}
   q_s = \sum q_i
   \end{equation}
   \hfill (2.4)

2. the number of discharges observed in one phase window (pulse count):
   \begin{equation}
   n = \sum i
   \end{equation}
   \hfill (2.5)
2.1. **PARTIAL DISCHARGE QUANTITIES**

![Diagram](image)

*Figure 2.3:* The discharge parameters \( q_i \) and \( \phi_i \) in time window \( i \).

3. the average value of discharges observed in one phase window (mean pulse height):

\[
q_n = \frac{q_i}{n} \tag{2.6}
\]

4. the maximum value of discharges observed in one phase window (maximum pulse height):

\[
q_m = \text{MAX}(q_i) \tag{2.7}
\]

where \( q_i \) is the discharge magnitude in a phase window during one voltage cycle and \( i = 1 \) if a discharge pulse occurs in the phase window, \( i = 0 \) if no discharge pulse occurs.

These quantities observed throughout the whole angle axis result in the following four distributions as function of the phase angle \( \phi_i \) (figure 2.4) [61]:

1. The discharge amount distribution \( H_{qs}(\phi) \) which represents the sum of the discharge magnitudes in each phase window as a function of the phase angle. *This quantity was not expected to yield much information and was not further studied in this thesis.*

2. The pulse count distribution \( H_n(\phi) \) which represents the number of the observed discharges in each phase window as a function of the phase angle.
Figure 2.4: Diagrams of phase-position quantities processed for two cycles of a.c. voltage.
3. The mean pulse height distribution $H_{qn}(\varphi)$ which represents the average amplitude in each phase window as a function of the phase angle. $H_{qn}(\varphi)$ is derived from the total discharge amount in each phase window divided by the number of discharges in the same phase window.

4. The maximum pulse height distribution $H_{qm}(\varphi)$ which represents the maximum value of discharges observed in each phase window as a function of the phase angle. *This quantity is not further studied in this thesis, but is regarded to be of interest in the future.*

All these deduced quantities can be observed as a function of time. The time behavior of $q_{\text{max}}(t)$, $N_q(t)$ and $U_{\text{inc}}(t)$ contains valuable information on the condition of the dielectric. This kind of measurement is often applied in making routine measurements [10]. It is known that variations in partial discharges occurs, both in the magnitude and in the temporal behavior of the discharges [62]. This is partly caused by statistical variations in the discharge phenomenon itself and it is partly the result of changes in the discharge site. By measuring pulse distributions of apparent charge $H(q)$ and discharge energy $H(p)$, it is possible to obtain information on the cause of the discharges [33,55,62]. Thus the distribution $H(q)$ can often be regarded as a "finger-print" of the discharge behaviour of insulating systems and can be associated with discharge sources [41,60].

The degradation of a dielectric by partial discharges is accompanied by energy transfer [55]. This energy supplied is equal to a product of the apparent discharge $q_i$ and the discharge ignition voltage $U_i$. That is to say, degradation is not only dependent on $q_i$ but also on $U_i$. And $U_i$ in the sinus is related to the phase angle $\varphi_i$. Therefore, more powerful description of destructive discharge processes can be expected by quantities which are a function of phase angle $\varphi_i$. In this case, the phase angle values $\varphi_i$ are combined with the discharge magnitude or repetition rate of discharges [33]. Further, these quantities give more detailed information about the sequences of partial discharges during the voltage cycle. This kind of observations has to date been determined with specialized measuring circuits and is in use on a small scale only [8].
Twenty-three years ago it had already been shown that observation of the discharge magnitude as a function of the phase angle is a good means to analyze different discharge patterns (figure 2.5) [32]. This figure shows the timing of discharges by a ramp rate voltage, related to the phase angle of this voltage. By means of an electronic circuit, the discharges were superimposed as light spots on a circle. Further, the radius of the circle depends on the magnitude of the test voltage and the position of a light spot on the circle is related to the phase angle. Based on these oscillographic pictures, the differences between different discharge sources are evident, but these profiles are not easy to evaluate.

According to several authors, the time behaviour of the pulse count distribution $H_n(\varphi)$ and that of the mean pulse height distribution $H_{qn}(\varphi)$ (figure 2.6) provide a good description of changes in discharge patterns [32,62,67,68,73]. The time behaviour of the $H_n(\varphi)$ distribution contains information on the intensity of discharges as a function of their inception phase angle. This allows the recognition of discharge sources and their behaviour in time [69,65,66]. The $H_{qn}(\varphi)$ quantity allows noise reduction because of the difference between the statistical characteristics of discharge pulses and that of noise pulses, both with regard to the phase angle [61].

It is known that each discharge source with its geometry, location in
Figure 2.6: Variations in $H_{q_n}(\varphi)$ and $H_n(\varphi)$ quantities processed in the course of time.
insulation, dielectric properties and applied field is characterized by a specific sequence of discharges. Analysis of phase angle quantities is thus a good means of discriminating between different discharge sources.

**STATISTICAL OPERATORS**

Quantities of the third group will be termed statistical operators: they provide the analysis of some of the deduced quantities from the second group. We can say that the \( H_{qn}(\varphi) \) and \( H_n(\varphi) \) distribution profiles provide important information about the dielectric containing partial discharges, but these profiles are not easy to evaluate. The use of computer-aided analysis makes is possible to process these quantities. Therefore, in 1978, with the intent to describe the distribution profile of \( H_{qn}(\varphi) \), the skewness of a distribution was experimentally adopted [67].

It is known from literature that in the case of a single defect, discharge quantities can be fairly well described by a normal distribution process [70]. Therefore to get a better evaluation of \( H_{qn}(\varphi) \) and \( H_n(\varphi) \) quantities, several statistical parameters can be used. They are here termed statistical operators. Assume for a discrete distribution function \( f(x) \) [70]:

\[
f(x) = P(X = x_i) = p_i \tag{2.8}
\]

where \( P \) is the probability; \( x_i \) is the discrete value and \( p_i \) is the probability value for \( x_i \). The following moments \( \mu_k \) of a distribution can be defined:

\[
\mu_k = \sum(x_i - a)^k \cdot p_i \tag{2.9}
\]

- **first moment**: \( \mu \) - mean value of a distribution; \( k=1, a=0 \)

\[
\mu = \sum x_i \cdot p_i \tag{2.10}
\]

- **second moment**: \( \sigma^2 \) - variance of a distribution; \( k=2, a=\mu \)

\[
\sigma^2 = \sum(x_i - \mu)^2 \cdot p_i \tag{2.11}
\]
2.1. PARTIAL DISCHARGE QUANTITIES

- **third moment**: skewness $Sk$ - indicator of the asymmetry of a distribution as compared to a normal distribution; $k=3, a=\mu$

$$Sk = \frac{\sum (x_i - \mu)^3 \cdot p_i}{\sigma^3} \quad (2.12)$$

- **fourth moment**: kurtosis $Ku$ - indicator of the sharpness of a distribution as compared to a normal distribution; $k=4, a=\mu$

$$Ku = \frac{\sum (x_i - \mu)^4 \cdot p_i}{\sigma^4} - 3 \quad (2.13)$$

The third and the fourth moments about the mean are significant with respect to the shape of the distribution [71]. They can therefore be used to characterize the distribution $H_{qn}(\varphi)$ and $H_n(\varphi)$ more precisely.

- The skewness $Sk$ indicates the asymmetry of the distribution. $Sk$ will be zero for a symmetric distribution, positive when the distribution is asymmetric to the left, and negative when the distribution is asymmetric to the right, see figure 2.7.

- The kurtosis $Ku$ indicates the degree of "peakedness" or sharpness of the distribution. Kurtosis $Ku$ is zero for a normal distribution. For a sharper than normal distribution $Ku$ is positive, and if the distribution is flatter than a normal distribution the $Ku$ is negative (figure 2.7).

As discussed previously, the discharges during a voltage cycle occur in two sequences: for each half of the voltage cycle separate discharge patterns can be found. Therefore the $H_{qn}(\varphi)$ and $H_n(\varphi)$ quantities are characterized by two distributions: for the positive half of the voltage cycle $H_{qn}^+(\varphi), H_n^+(\varphi)$ and for the negative half of the voltage cycle $H_{qn}^- (\varphi), H_n^- (\varphi)$. Consequently each quantity can be described by two skewness values $Sk^+, Sk^-$ and two kurtosis values $Ku^+, Ku^-$. The distributions $H_{qn}(\varphi)$ and $H_n(\varphi)$ are also characterized by their mean value, their inception phase and the number of peaks. Therefore more statistical parameters can be defined, enabling us to compare the mean values, the inception phase and the number of peaks.
Figure 2.7: Typical distribution profiles and their skewness \( Sk \) and kurtosis \( Ku \) values.
in the both positive and the negative half of the voltage cycle. To study these differences between the distributions $H^+_q(\varphi)$ and $H^-_n(\varphi)$ both halves of the voltage cycle the following statistical operators have been introduced by the author:

- **Discharge asymmetry $Q$** as the quotient of the mean discharge level in the positive and in the negative half of voltage cycle:

$$Q = \frac{Q^-_s / N^-_q}{Q^+_s / N^+_q}$$

(2.14)

where $Q^\pm_s$ is the sum of the discharge magnitudes in the positive half or negative half of the voltage cycle, and $N^\pm_q$ is the number of discharges in the positive or in the negative half of the voltage cycle. The sum of discharges per half cycle $Q^\pm_s$ is:

$$Q^\pm_s = \sum q^\pm_i$$

(2.15)

where $q^\pm_i$ is the magnitude of apparent charge in phase windows in the positive or the negative half of the voltage cycle.

- **Phase asymmetry $\Phi$** to study the difference in inception voltage in the positive and negative half of the voltage cycle:

$$\Phi = \frac{\varphi^-_{inc}}{\varphi^+_{inc}}$$

(2.16)

where $\varphi^\pm_{inc}$ is the inception phase in the positive or in the negative half of the voltage cycle. *This quantity is not further studied in this thesis.*

- **The cross-correlation factor $cc$**, known from literature [72], to evaluate the difference in shape of distributions $H^+_q(\varphi)$ and $H^-_n(\varphi)$. The following formula is used to calculate the cross-correlation factor $cc$:

$$cc = \frac{\sum x_i y_i - \sum x_i \sum y_i / n}{\sqrt{[\sum x_i^2 - (\sum x_i)^2 / n] [\sum y_i^2 - (\sum y_i)^2 / n]}}$$

(2.17)
where $x_i$ is the mean discharge magnitude in a phase window in the positive half of the voltage cycle; $y_i$ is the mean discharge magnitude in the corresponding phase window in the negative half of the voltage cycle and $n$ is the the number of phase-positions per half cycle.

A cross-correlation $cc$ equal to 1 means a 100% shape symmetry and a value of 0 indicates total asymmetry. However, $cc$ tells us nothing about the height of the distribution. For that purpose we use the discharge asymmetry $Q$ or phase asymmetry $\Phi$. Both discharge asymmetry $Q$ and phase asymmetry $\Phi$ are defined in such a way that they are equal to 1 in the case of fully symmetric distributions and smaller than one in the case of non-symmetric ones. Thus several asymmetry factors can be easily combined (with equal weight-factors) by multiplication. Therefore the following operator has been introduced by the author:

- **The modified cross-correlation factor $mcc$**, to evaluate the differences between discharge patterns in the positive and the negative voltage cycle. This can be defined as a product of some of following statistical operators: the phase asymmetry $\Phi$, the discharge asymmetry $Q$ or the cross-correlation factor $cc$:

$$mcc = \Phi \cdot Q \cdot cc.$$ \hspace{1cm} (2.18)

As in this thesis the statistical operator $\Phi$ was not further studied the $mcc$ factor in experiments was processed for the case $\Phi=1$.

- **The number of peaks $Pe$** in order to distinguish between a distribution with a single top and a distribution with several tops:

$$Pe = \sum \text{peak}(x_i)$$ \hspace{1cm} (2.19)

where $\text{peak}(x_i)=1$ if the distribution $H_{\text{qn}}(\varphi)$ or $H_{\text{n}}(\varphi)$ in the phase window $x_i$ is characterized by a local top. The local top
2.1. PARTIAL DISCHARGE QUANTITIES

of a distribution in the phase window \( x_i \) can be defined if the following conditions are valid:

\[
\frac{dy_{i-1}}{dx_{i-1}} > 0 \quad \text{and} \quad \frac{dy_{i+1}}{dx_{i+1}} < 0
\]  

(2.20)

where the \( \frac{dy_{i+1}}{dx_{i+1}} \) is the differential coefficient before or after the possible local top of a distribution.

CONCLUSIONS

The use of different partial discharge quantities has been introduced throughout the years [8,11]. Partial discharge quantities presented in this section were classified in three main groups: basic quantities, deduced quantities and statistical operators, these quantities are shown in figure 2.8.

<table>
<thead>
<tr>
<th>BASIC QUANTITIES</th>
<th>FOR ONE DISCHARGE</th>
<th>FOR HALF CYCLE OF TEST VOLTAGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>( q_i )</td>
<td>apparent charge</td>
<td>( N_q ) number of discharges</td>
</tr>
<tr>
<td>( t_i )</td>
<td>inception phase</td>
<td>( Q_i ) integrated discharge value</td>
</tr>
<tr>
<td>( U_i )</td>
<td>ignition voltage</td>
<td>( W_i ) integrated energy value</td>
</tr>
<tr>
<td>( q_d )</td>
<td>supplied discharge energy</td>
<td>( U_{in} ) inception voltage</td>
</tr>
<tr>
<td>( \Delta q_d )</td>
<td>dissipated discharge energy</td>
<td>( U_{ext} ) extinction voltage</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>DEDUCED QUANTITIES</th>
<th>AS A FUNCTION OF TIME FOR THE POSITIVE AND THE NEGATIVE HALF OF THE VOLTAGE CYCLE</th>
<th>AS A FUNCTION OF PHASE ANGLE</th>
</tr>
</thead>
<tbody>
<tr>
<td>( N_{q+i} )</td>
<td>number of discharges</td>
<td>( H_{q+i} ) discharge amount distribution</td>
</tr>
<tr>
<td>( Q_{i+1} )</td>
<td>integrated discharge value</td>
<td>( H_{p+i} ) pulse count distribution</td>
</tr>
<tr>
<td>( W_{i+1} )</td>
<td>integrated energy value</td>
<td>( H_{t+i} ) mean pulse height distribution</td>
</tr>
<tr>
<td>( U_{ext+i} )</td>
<td>extinction voltage</td>
<td>( H_{max+i} ) maximum pulse height distribution</td>
</tr>
<tr>
<td>( q_{max+i} )</td>
<td>mean of apparent charge</td>
<td>( \Phi_{max+i} ) mean of discharge energy</td>
</tr>
<tr>
<td>( q_{i+1} )</td>
<td>max. discharge magnitude</td>
<td>( \Phi_{max+i} ) max. discharge energy</td>
</tr>
<tr>
<td>( H_{1+i} )</td>
<td>distribution of discharge magnitudes</td>
<td>( H_{max+i} ) distribution of energy magnitudes</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>STATISTICAL OPERATORS</th>
<th>( \Delta k ) skewness</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( \Delta k ) - kurtosis</td>
</tr>
<tr>
<td></td>
<td>( \Omega ) - discharge asymmetry factor</td>
</tr>
<tr>
<td></td>
<td>( \phi ) - phase asymmetry factor</td>
</tr>
<tr>
<td></td>
<td>( \rho_c ) - cross-correlation factor</td>
</tr>
<tr>
<td></td>
<td>( \text{modcorr} ) - modified cross-correlation factor</td>
</tr>
<tr>
<td></td>
<td>( P_c ) - number of peaks</td>
</tr>
</tbody>
</table>

Figure 2.8: Partial discharge quantities.
It is evident that each quantity gives partial information only; the analysis in this section has shown that simultaneous observation of several discharge quantities may lead to a better evaluation. Based on this supposition a diagnostic system for discharge measurements is proposed, using a systematic processing of the discharge quantities (figure 2.9). The main aim of this diagnostic system is to find a good system for the recognition of discharge sources. The study will be concentrated on four main objectives:

- the development of a discharge analyzer (chapter 3).
- a study of the correlation between statistical operators and the type of defects that cause discharges (chapters 4, 5, 6 and 7).
- the development of a system for the recognition of these defects, based on the studies above (chapter 8).
2.2 AUTOMIZED REGISTRATION OF DISCHARGES

- the application of these results to same of technical objects (chapter 9).

2.2 Automized registration of discharges

Partial discharge measurement are performed by routine actions such as the choice of test conditions, the adjustment of the detection apparatus to the circuit, the calibration of the circuit, etc. After this a computer-aided measurement is required to obtain and analyze the discharge quantities given in section 2.1. The following three procedures are discussed for the development of the discharge analyzer:

1. Measurement
2. Registration
3. Evaluation.

MEASUREMENT

The measurement procedure of partial discharges can also be divided in three stages (figure 2.10):

1. Adjustment of the measurement circuit.

Before a measurement starts the adjustment of the measurement circuit takes place. The following test conditions are important:

- kind of test voltage: increasing voltage or constant voltage and the magnitude of the test voltage
- duration of the test: a short test or an endurance test
- the characteristics of the sample: capacitance, expected discharge level and expected discharge intensity.

These test conditions are basic for the choice of the following parameters:
Figure 2.10: Partial discharge measurement procedures.
2.2. AUTOMIZED REGISTRATION OF DISCHARGES

- sampling rate \( F_s \) of the digital-analog conversion
- amplification rate \( v_a \) of the discharge signals
- discharge magnitude \( q_k \) for the calibration of measured signals
- triggering moment \( \varphi_t \) in relation to test voltage
- test time \( T_T \)
- number of quantities choice processed during test \( Q_N \).

2. Measurement and storage of voltage and discharge signals

After the measurement has been started the signal, test voltage and discharge impulses, are detected and continuously registered. For this purpose the \( \varphi_t \) and \( v_a \) parameters are used. Then, making use of \( F_s \) the digitalization and the storage in the buffer memory of the data acquisition unit take place. After the discharge sequence and voltage signal have been stored in the buffer memory, the data transport from this memory to the computer memory follows. Finally, the acquisition unit can start with the next measuring cycle.

3. Processing of measuring data

In the third stage the data from the computer memory are processed. First the reconstruction and the determination of the discharge sequence takes place making use of the calibration magnitude \( q_k \). Further, the processing of the basic quantities \( Q_N \) occurs, followed by storage in the memory and the calculation of deduced quantities take place. In an endurance test, the reduction of data is necessary because of the limited memory capacity. After the processing of these data has been finished, the display of their quantities takes place. Afterwards, the next data transport from the acquisition unit and the processing can take place.

REGISTRATION
For the automated registration of discharges the following characteristics are of importance:
CHAPTER 2. AUTOMIZED ANALYSIS OF DISCHARGES

- Adjustment of the sampling frequency of the analog-digital conversion to the resolution of the detection circuit.

- Continuous registration of the discharge sequences throughout the test.

For many years two principal methods for detecting partial discharges have been used. These two methods will be discussed here (figure 2.11).

![Diagram](image)

**Figure 2.11:** Basic methods for automated discharge detection.

1. In the first method, the partial discharges are detected with regard to their real time occurrence of 10ns or less [74]. A detector with a bandwidth of 100MHz or more is then applied. In consequence, a sampling frequency of 200MHz or more is required for the analog-digital conversion. In this method, the storage of only 20ms duration of discharge sequence (this is 1 cycle of 50Hz voltage) requires a memory capacity of 4 Mbyte.
Further, the calculation of the basic quantities requires a realistic large software and hardware support. This kind of registration is chiefly used for the fundamental study of partial discharges, where the interest concentrates on the exact registration of a single pulse.

2. In the second method the discharge signal is integrated; the frequency spectrum of the discharge signal is reduced to some hundreds of kHz. In consequence, the sampling frequency of the analog-digital converter is limited to 1MHz or less. It follows that much less memory space is required for the storage of this data. At a sampling frequency of 1MHz the memory capacity of 4 Mbyte allows the registration of 4s duration of discharge sequence (this equals 200 cycles of 50Hz voltage). Further, the computer processing can concentrate on the calculation of basic and deduced quantities.

Further, there is also a means to determine different basic quantities before digitalization. By means of electronic circuits: multiplicators, integrators, comparators and multi-channel analyzers the supplied energy, integrated values of discharge and energy, the inception and terminating voltage and the distributions of charge and energy can be determined.

In this thesis the second method is used as shown in figure 2.11 (the shaded part). It aims to a computer-aided system for partial discharge measurements in industrial tests. The further study will concentrate on the use of conventional discharge detection with a bandwidth of 100 to 400 kHz, which is internationally accepted for tests of insulating systems [75].

**PROCESSING**

The following two basic systems to process the discharge measurements can be chosen [76]. The first one is the batch system. In this system the measurement input data are collected throughout the test and their processing and output are made after the test has been finished. The second method is the on-line system. In this system the processing of input data occurs during the test. The system provides output information while the test is running.
The foregoing discussion has made it clear that the registration of discharge measurements is limited by the memory capacity. Therefore, the *batch* processing can handle short tests only: a few seconds. In *on-line* processing the data are transported in blocks during the test from the acquisition unit to the computer memory and are processed.

In view of these considerations, this thesis will concentrate on the use of *on-line* processing. With regard to time, two situations can be distinguished here (figure 2.12). In the first, there are no breaks during the registration. The processing times are not longer than the measuring times (figure 2.12a). In the second, some interruptions are allowed as the processing of data requires more time than the registration (figure 2.12b).

![Diagram](image)

**Figure 2.12:** Time relations between registration and processing.

a) registration without interruptions

b) registration with interruptions

In defining the requirements, the following objectives are important:
2.2. AUTOMIZED REGISTRATION OF DISCHARGES

1. The discharge analyzer has to process and to display the discharge quantities on-line, during the test.

2. To guarantee that no discharge pulse is lost the continuity of the measuring of discharges and their processing is required. It means that the elapsed time of processing routines has to be adjusted to the measuring time.

3. To allow for this timing requirement the processing and display of data can be divided into two stages:
   - The basic quantities and a part of the deduced quantities are calculated and displayed on-line. Thus, a fast insight in the discharge process is available.
   
   The basic quantities require much less memory space than the input data. In fact, the storage of the input data accumulated during one cycle of 20ms requires many kbyte memory, but, the storage of the basic quantities of this on-line sequence requires only bytes instead of kbyte of memory.

   **For instance:** a sampling frequency of $F_s = 500kHz$ and a memory capacity $M_c = 2 Mbyte$ allow a 204 seconds registration of input data. After the calculation the same memory capacity (2 Mbyte) allows a 34-minute registration of 10 different basic quantities.

   - The other deduced quantities and the statistical operators are prepared during the test, but they are processed and displayed in off-line mode after the test has been finished.

4. The operating system of the discharge analyzer must cope with all possible fluctuations of the discharge process.

5. The storage in the memory of deduced quantities has to be such, that these quantities are accessible for an extensive statistical analysis.

6. For long endurance tests, a larger memory capacitance is required. Alternatively, data reduction can be applied, in which
way one representative value is obtained for several cycles, e.g.
the average or the maximum value for a number of cycles. The
number of these cycles representing in one cycle is termed the
reduction factor \( R \).

For instance: a memory capacity \( M_c = 2 \text{ Mbyte} \) and a reduction
factor \( R = 5 \) allow 2 hours and 50 minutes of registration of
10 basic quantities instead of 34 minutes without reduction.

Generally there is a relationship between the available memory ca-
pacity \( M_c \), the number of quantities processed \( Q_N \), the measuring
time \( T_T \) and the reduction factor \( R \)

\[
T_T \cdot Q_N \sim M_c \cdot R. \quad (2.21)
\]

**CONCLUSIONS**

For the development of a partial discharge analyzer (based on con-
ventional detection methods with a bandwidth of about 400 kHz)
several design choices have been made:

1. Characteristic parameters have been chosen, derived from the
measurement procedures of discharge detection.

2. The sampling frequency of the analog-digital converter is lim-
ited to 1MHz or less.

3. The basic quantities and part of the deduced quantities will
be processed and displayed on-line. The other deduced quan-
tities and also the statistical operators will be processed and
displayed off-line.

4. For most endurance tests, the storage of the calculated quanti-
ties is limited by the memory capacity. Therefore a reduction
of data is required.
Chapter 3
Configuration of the discharge analyzer

Based on the objectives presented in section 2.2 a discharge analyzer has been developed. The set-up will be discussed here with respect to:

1. *Hardware components*: for this purpose commercially available equipment has been used. The functional use is described so that these components can be replaced by other, but compatible, equipment.

2. *Software components*: specialized programs have been developed for partial discharge analysis. The user interface and the functional structure are described.

These two groups will be discussed here.

**HARDWARE COMPONENTS**
The hardware contains a high-voltage test circuit, partial discharges detection circuit, a data acquisition unit and a personal computer (figure 3.1).
The high-voltage test circuit consists of a 50Hz 100kV high-voltage transformer: a coupling capacitance $C_k$ of 200pF is used to facilitate the passage of the high-frequency current impulses.
To measure partial discharges, a classic balanced detection system is used. This system contains a detection bridge and a partial discharge detector of Haefely Type 560. The bandwidth has a lower limit of 40kHz and an upper limit of 400kHz. To measure the high voltage
a capacitance voltage divider with ratio 5000:1 is used. The high-voltage sine wave is also used to trigger the acquisition unit. To digitize the discharge signal and that of the high voltage a transient recorder, DataLab DL 919, is used. This transient recorder provides a maximal sampling frequency of 20MHz and has access to two 4 kbyte memory buffers. In order to synchronize the discharge signal with a 50Hz time base, the transient recorder is triggered by an impulse $\varphi_t$ delivered from the high-voltage sine wave. The discharge signal from the detector is adjusted to the transient recorder by performing an adjustable pulse-height to pulse-width conversion. In this way the Nyquist theorem is satisfied. Further, the transient recorder is connected to an Olivetti M24 personal computer by means of a digital I/O Interface PIO12. The main functions of the computer are:

- starting the A/D conversion
- writing the digitized data from the transient recorder buffer into the work space of the computer memory
- controlling the measuring time
- processing, storing and displaying the discharge quantities.
Further, after the measuring has been finished, the deduced quantities and the statistical operators are processed, stored and displayed. During processing, the work space of the computer memory 450 kbyte is used by software routines and for storage the discharge quantities. After the test has been finished, the processed quantities are stored on a 20 Mbyte hard disk which can also be written on a 360 kbyte floppy unit.

In order to shield off electromagnetic fields and earth interferences, the configuration is placed inside an aluminum cage, while optimal grounding is maintained.

SOFTWARE COMPONENTS
The development of the software components is based on off-line and on-line processing (figure 3.2). The off-line functions are responsible for the activities before and after the measurement period. The on-line functions are responsible for the activity during the measurement period: controlling, digitizing, processing and displaying routines. In view of these considerations the following four phases are discussed here:

![Diagram](image)

**Figure 3.2:** Functional structure of the software components.

1. Pre-measuring activities
2. Measuring

3. Post-measuring activities

4. Statistical analysis.

The software routines for phases (1), (3), and (4) work in the offline mode, thus without strong requirements on the elapsed times. Therefore, these routines could be developed in one of the problem-oriented languages: in this case the Microsoft QuickBASIC Version 4.50. has been used. To execute these routines two EXE stand-alone programs are compiled. For the phases (1) and (3) a 120 kbyte program PDM2.EXE has been developed. For phase (4) a 90 kbyte program SPDM2.EXE has been developed.

In contrast, the routines for phase (2) work in the on-line mode, with strong requirements on the elapsed times (section 2.2). Therefore, these routines have been developed in a machine language: in this case the Microsoft Macro Assembler Version 4.0 has been used.

To execute these routines two BIN programs have been compiled as subroutines to PDM2.EXE: for controlling, digitizing and displaying during the test, a 3.1 kbyte program, and for processing the discharge quantities, a 2.6 kbyte program. These BIN programs require a work memory of 49 kbyte.

The functional description of these phases will be discussed here.

Pre-measuring activities

Before the test starts the adjustment of the parameters stated below takes place, as well as the calibration of the detection circuit. To start the measuring and processing procedure the following parameters are needed:

- Sampling frequency $F_s$ [kHz]; in order to calculate the number of phase windows for one cycle of the 50Hz high voltage.

- Noise suppression factor $D_n$ [%]; in order to discriminate between system noise and discharges impulses, the ratio of the noises with regard to the maximal discharge measured is required.
• *Time mode*; to control the duration of the test
  a) long time test: test duration, $T_T [\text{min}]$
  b) short time test: number of 50Hz cycles, $T_c [\text{number}]$.

• *Quantities choice $Q_N$ [list]*: an inventory of basic and deduced quantities to be processed during the test.

• *Number of distributions $M_p$ [number]*; the number of distributions of quantity which are calculated during the test period $T_T$.

The memory for the storage of deduced quantities is organized in two ways. The nine deduced quantities are stored as a function of time in the 108 kbyte memory space called *Memory page $F_x$* (figure 3.3). For each quantity a volume of 12 kbyte is accessible. It follows (see relationship (2.21)), that in the case of endurance tests storage of data up to $T_T = 20$ minutes is possible. For longer test periods a reduction will be applied: for test period $T_T$ up to 40 minutes the reduction factor $R = 2$, up to $T_T = 60$ minutes $R = 3$ etc.

![Memory page $F_x$ diagram](image)

*Figure 3.3:* Memory organization of the storage of discharge quantities.

The four deduced quantities are stored as distribution functions in the 24 kbyte memory space called *Memory page $H_x$* (figure 3.3). For
each of the quantities \( H(q) \) and \( H(p) \), 4 kbyte are accessible, and for each of the quantities \( H_q(\varphi), H_n(\varphi) \), 8 kbyte are accessible. In the case of several distributions of one quantity \( M_p > 1 \) the test time will be subdivided in \( M_p \) intervals. For each interval one memory page \( M_p \) will be created. For example, the distributions shown in figure 2.6 were stored in five \( H_x \) memory pages; after each fifth minute a new memory page \( H_x \) was used.

To identify the measured discharges in picocoulombs, calibration of the system is required. Therefore, a known discharge amplitude \( q_k \) is injected in the sample. A discharge resolution factor \( M_q \) is calculated as follows:

\[
M_q = \frac{q_k}{X_{RAM}} \quad (3.1)
\]

where the \( X_{RAM} \) is the digitized memory value of \( q_k \). The discharge resolution factor \( M_q \) represents the smallest difference in discharge magnitude (in picocoulombs) that can be detected.

Based on noise suppression \( D_n \) and the discharge resolution factor \( M_q \) the sensitivity is calculated.

To identify the test voltage in kVolts, voltage calibration of the system is required. Therefore, a known voltage amplitude \( V_k \) is applied and a voltage resolution factor \( M_v \) is calculated as follows:

\[
M_v = \frac{V_k}{X_{RAM}} \quad (3.2)
\]

where the \( X_{RAM} \) is the digitized memory value of \( V_k \). The voltage resolution factor \( M_v \) represents the smallest difference in voltage (in kVolts) that can be detected.

By multiplying the factors \( M_q \) and \( M_v \), the energy resolution factor \( M_p \), the smallest detectable difference in energy magnitude, is calculated in nanojoules:

\[
M_p = M_q \cdot M_v. \quad (3.3)
\]

Now the test can be started. First the work memory is cleared and filled with values 0. Second digitizing is started. If no partial discharges occur at the beginning of the test, the analyzer registers
the time until discharges occur. After that the registration and the processing procedures are started.

The registration takes place for the period which is programmed by the time mode. During this period the user can interrupt the registration only by using interrupt keys. The following interruption functions are possible:

- *Premature stop of the registration:* the measuring and registration will be finished.

- *Temporary break of registration:* the measuring and registration are temporary interrupted and can be continued.

- *Change of input parameters:* earlier test parameters can be changed and the registration can be continued.

- *Change of resolution factors:* the resolution factors \( M_p, M_q \) and \( M_v \) can be changed and the registration can be continued.

**Measuring**

For a better explanation of these software functions, the procedures of measuring and processing will be discussed here. The test time is divided into many intervals, called transfer interval \( T_m \) (see in section 2.2 the figure 2.12). During this interval \( T_m \), the discharge input data are written into a buffer memory of the acquisition unit. This length of transfer interval \( T_m \) is defined as:

\[
T_m[ms] = \frac{B_m[byte]}{F_s[kHz]} \tag{3.4}
\]

where \( B_m \) is the capacity of buffer memory in the acquisition unit and \( F_s \) the sampling frequency of the A/D converter. The number of cycles \( N_c \) of the 50Hz voltage, alternatively 60Hz, registered during the transfer intervals \( T_m \) can be calculated as below:

\[
N_c = \frac{T_m[ms]}{20[ms]} \tag{3.5}
\]

To register at least 20ms of the discharge sequence during the transfer interval \( T_m \) follows from equations (3.4) and (3.5) the permissible sampling frequency \( F_{ps} \):
\[ F_{ps}[kHz] = \frac{B_m[byte]}{N_c \cdot 20[ms]} \] (3.6)

where \( B_m \) is the capacity of the buffer memory and \( N_c \) the number of cycles of the 50Hz voltage, alternatively 60Hz. When the transient recorder DL919 uses two buffers of 4 kbyte, this means that the permissible sampling frequency \( F_{ps} \) is 410kHz.

The processing comprises the following:

- First a test for the existence of partial discharges is made; if no discharges occur, the calculation of basic quantities is not performed.

- If discharges occur, \( N_c \) cycles of discharge input data are reduced to one cycle.

- For this single cycle of input data the basic quantities are calculated.

- Using the quantities-choice \( Q_N \) the following basic quantities for the positive and the negative half of the voltage cycle of 50Hz high-voltage can be calculated:
  - the maximum discharge magnitude: \( q_{max} \)
  - the mean discharge magnitude: \( q_{mean} \)
  - the maximum discharge energy: \( p_{max} \)
  - the mean discharge energy: \( p_{mean} \)
  - the integrated value of discharge: \( Q_s \)
  - the integrated value of discharge energy: \( W_s \)
  - the number of discharge: \( N_q \)
  - the inception voltage: \( U_{inc} \)
  - the terminating voltage: \( U_{term} \).

- Next, the following distributions are derived from basic quantities:
- the discharge amount distribution: $H_{qs}(\varphi)$
- the pulse count distribution: $H_n(\varphi)$
- the discharge number distribution: $H(q)$
- the discharge energy distribution: $H(p)$.

• After the calculation, the storage of the quantities take place. For the storage of the basic quantities, the memory page $F_x$ is used, whereas the storage of the distributions takes place in the memory page $H_x$.

• In addition the numeric and graphic display is started (figure 3.4).

• Finally, a control program checks the following four statuses of the test:

  * **Interrupting the test:** if interrupt keys have been active the interrupt routines will be performed.

  * **Changing over to new memory page $H_x$:** from now on the basic quantities will be written as new distributions on the next memory page $H_x$.

  * **Continuing the test:** transport of discharge input data from the acquisition unit and their processing as above described.

  * **Stopping the test:** end the registration. All calculated quantities and measuring parameters are stored on the computer hard disk.

**Post-measuring activities**

After the test has been finished the display of deduced quantities and the manipulation of measuring files take place.

To display the deduced quantities, four types of graphic layouts with linear scales have been developed (Figure 3.5).
Figure 3.4: Layout of the analyzer screen during the test.

Figure 3.5: Screen layouts for display of discharge quantities.

a) quantities as a function of time
b) distribution functions
c) phase-position quantities
d) multiple presentation
• Each quantity from the memory page $F_x$ is displayed by two curves: one for the positive half and one for the negative half of the voltage cycle (figure 3.5a). Therefore, a display is chosen, where the $Y$ axis is divided into two parts and where the $X$ axis represents the time.

• For the $H(q)$ and $H(p)$ quantities, a display is used, where the $X$ axis represents the discharge values in picocoulombs or energy values in nanojouls. The $Y$ axis represents the occurrence of discharge values and energy values (figure 3.5b).

• For the display of the deduced quantities as a function of the phase, a choice had to be made between a three-dimensional and a two-dimensional presentation. According to [77] a combination of $H_{qs}(\varphi)$, $H_{qn}(\varphi)$ and $H_n(\varphi)$ can be displayed as a three-dimensional distribution. This has the advantage of visible strength. However, because of its complexity, such a picture is more difficult to analyze. Therefore, the choice has been made to display $H_{qs}(\varphi)$, $H_n(\varphi)$ and $H_{qn}(\varphi)$ as two-dimensional distribution functions. For this purpose, the display is used where the $X$ axis represents the phase angle. The $Y$ axis represents the occurrence of discharges in the case of $H_n(\varphi)$ and the discharge values in picocoulombs in the cases of $H_{qs}(\varphi)$ and $H_{qn}(\varphi)$ (figure 3.5c). Because, during the test, only the quantities $H_{qs}(\varphi)$ and $H_n(\varphi)$ are calculated, the quantity $H_{qn}(\varphi)$ has to be calculated as follows:

$$H_{qn}(\varphi) = \frac{H_{qs}(\varphi)}{H_n(\varphi)}. \quad (3.7)$$

• To compare different quantities on the same $X$ axis (the distributions of one quantity registered on many memory pages $H_x$) a display is used where the $Y$ axis can be divided into more parts (figure 3.5d).

The manipulation of the test files comprises two procedures:

• The saving in test data files using a 360 kbyte floppy driver, of all processed quantities and their test parameters. To characterize these data files, an identification name is created.
The loading of other data files into the computer memory. Using the identification name of these files, all processed quantities and their test parameters are loaded in the 450 kbyte workspace of the analyzer.

Statistical analysis

After the test has been finished, the processing of statistical operators, their display and their storage can be started.

Two deduced quantities are analyzed: the mean pulse-height phase distributions $H_{qn}(\varphi)$ and the pulse-count phase distributions $H_n(\varphi)$. These quantities are characterized by two distributions: for the positive half of the voltage cycle $H_{qn}^+(\varphi)$, $H_n^+(\varphi)$ and for the negative half of the voltage cycle $H_{qn}^-(\varphi)$ and $H_n^-(\varphi)$. For these distributions the following statistical operators are calculated (see section 2.1.1):

- Skewness $Sk$: on $H_{qn}^+(\varphi)$, $H_n^+(\varphi)$, $H_{qn}^-(\varphi)$ and $H_n^-(\varphi)$.
- Kurtosis $Ku$: on $H_{qn}^+(\varphi)$, $H_n^+(\varphi)$, $H_{qn}^-(\varphi)$ and $H_n^-(\varphi)$.
- Discharge asymmetry factor $Q$: between $H_{qn}^+(\varphi)$ and $H_{qn}^-(\varphi)$.
- Phase asymmetry factor $\Phi$: between $H_{qn}^+(\varphi)$ and $H_{qn}^-(\varphi)$.
- Cross-correlation factor $cc$: between $H_{qn}^+(\varphi)$ and $H_{qn}^-(\varphi)$.
- Modified cross-correlation factor $mcc$: between $H_{qn}^+(\varphi)$ and $H_{qn}^-(\varphi)$.
- Number of peaks $Pe$: on $H_{qn}^+(\varphi)$, $H_n^+(\varphi)$, $H_{qn}^-(\varphi)$ and $H_n^-(\varphi)$.

In the case of $M_p$ memory pages $H_z$, several statistical operators $M_p$ can be calculated for each quantity. the result is that the time behaviour of the statistical operators can be analyzed in the case of $M_p > 1$ values of each quantity (figure 3.6).

After the calculation, all these statistical operators are displayed and they are saved in a statistical data file. To manipulate these files there exist the same possibilities as for measuring data files.
CONCLUSIONS

Based on the study of partial discharge quantities (section 2.1), and based on the choices made for an automated analysis (section 2.2), a discharge analyzer has been developed. This analyzer is composed of a conventional detection system, a commercial data acquisition unit and a personal computer (figure 3.7).

A software packet has been developed to register, to process, to store and to evaluate the partial discharge measurements. A schematic presentation of this analysis is shown in figure 3.8.

The analyzer provides partial discharge registration, both for short tests and for long-time endurance tests. After the test a statistical analysis by means of statistical operators is provided.

In the following chapters the discharge analyzer will be studied for its ability to recognize discharging defects.
Figure 3.7: Partial discharge detector and analyzer; the high-voltage circuit is located behind the wire screen.
Figure 3.8: Schematic presentation of partial discharge analysis.
Chapter 4
Analysis, general remarks

Frequently occurring discharges are corona, surface discharges, floating parts, void discharges and treeing. They occur in gaseous, liquid and solid mediums. Each of these discharge types will be analyzed and the recognition by statistics (section 2.1) will be tested. Physical models were made for this purpose, which can be divided into three main groups. Each group will be discussed in a separate chapter:

1. Discharges in gases (chapter 5):
   
   • corona in air
   • surface discharges in air and in $SF_6$
   • floating parts in air.

2. Discharges in liquid (chapter 6):

   • corona in oil
   • surface discharges in oil.

3. Discharges in solids (chapter 7):

   • discharges in cavities
   • treeing initiated by a conductor
   • treeing initiated by a cavity.
A discussion on the discriminating strength of the observed statistical operators is given in chapter 8. An application of these results to technical objects is presented in chapter 9 [78,79].

**PARTIAL DISCHARGE QUANTITIES**
All quantities presented in section 2.1 were tried out during the tests. Some of these quantities did not show a discriminative strength and were thus discarded. Eventually, the combination of the following deduced quantities and statistical operators was chosen:

- the maximum discharge magnitude $q_{max}(t)$
- the number of discharges $N_q(t)$
- the inception voltage $U_{inc}(t)$
- the mean pulse height distribution $H_{qn}(\varphi)$
- the pulse count distribution $H_n(\varphi)$
- the skewness $Sk$ on $H_{qn}^\pm(\varphi), H_n^\pm(\varphi)$
- the kurtosis $Ku$ on $H_{qn}^\pm(\varphi), H_n^\pm(\varphi)$
- the discharge factor $Q$ on $H_{qn}(\varphi)$
- the cross-correlation factor $cc$ on $H_{qn}(\varphi)$
- the modified cross-correlation factor $mcc = Q \ast cc$
- the number of peaks $Pe$ on $H_{qn}^\pm(\varphi), H_n^\pm(\varphi)$

**STATISTICAL RESPONSE**
In order to evaluate the results, a number of tests were carried out for each defect. Series of 8 to 23 observations of the same discharge source were made in order to estimate of the true population of each statistical operator. The next step was to determine if the values of a statistical operator obtained for a specific defect belong to the same population.

It is common practice to discard a sample as belonging to the same population when the sample is found to be outside the 90% or 95%
confidence interval of the true population. However, due to the fact that the estimation of these true populations will be based on a relatively small number of samples the scatter, and thus the width of the distributions will be rather large, resulting in a large overlap of different populations. In this situation it can be difficult to decide between two (or more) populations.

The problem can be solved by using the confidence interval covering the mean of the true population. The distribution of the means of a number of observations is narrower.

For each of the statistical operators, obtained with one type of defect, the mean value \( M_{so} \) was calculated. The \( C_{2.5\%} \) and \( C_{97.5\%} \) quartiles for the mean value \( M_{so} \) are equal to [71]:

\[
C_{2.5\%} = M_{so} - \frac{t \cdot s}{\sqrt{N}}; \quad C_{97.5\%} = M_{so} + \frac{t \cdot s}{\sqrt{N}} \quad (4.1)
\]

where \( M_{so} \) is the arithmetic mean of values of a statistical operator obtained from a series of \( N \) observations of one and the same type defect, \( s \) is the standard deviation of this series and \( t \) is a statistical test parameter depending on \( N \).

This 95% confidence interval covering the mean values of a statistical operators was chosen as representative for a defect, called in further text the statistical response of a defect. Examples of statistical response in the case of discharges in gases are shown in figures 5.6, 5.13, and 5.20. If a defect is analyzed the analysis takes in general 20 minutes, whereas 1 to 2 minutes would be sufficient to determine the statistical operators. Consequently, the mean value obtained in 20 minutes can be regarded as the mean of 10 to 20 values and can be directly compared with the above stated interval statistical response. In chapter 8.2 this technique is further worked out.

**MEASURING TIME**

All quantities were measured during a 20 minute test (except in the endurance tests with treeing discharges). The time interval of 20 minutes was chosen for two reasons:

- In the case of discharges in solid materials, the time interval was sufficient (in combination with the transfer intervals \( T_m \),
see in section 2.2 the figure 16b) to register the characteristics of the discharges.

- Based on the relationship (2.21) the time interval of 20 minutes was the upper limit of the measuring time \( T_T \) to register data with a reduction factor \( R=1 \) (see chapter 3). This method entailed no loss of information.

For all discharge sources, the \( H_{qn}(\varphi) \) distribution and the \( H_n(\varphi) \) distribution were calculated during the 20 minute test. To register changes in the discharge patterns by means of endurance tests with treeing discharges, the test time was divided into several intervals. For each interval, distribution \( H_{qn}(\varphi) \) and \( H_n(\varphi) \) were calculated. The number of these intervals was defined by the number of distributions \( M_P \) as discussed in chapter 3. The analysis of \( H_{qn}(\varphi) \) and \( H_n(\varphi) \) distributions by means of the chosen statistical operators was carried out off-line.

**MEASURING VOLTAGE**

All models were subjected to a constant a.c. test voltage. The test voltage was chosen at a level where no extinction of discharges was expected. The exact value of the voltage that was applied during the tests will be presented together with the measuring results.

**NOISE SUPPRESSION**

In order to discriminate between system noise [8] and discharge pulses, a noise suppression factor \( D_n \) is defined as:

\[
D_n[\%] = \frac{S_{\text{min}}}{S_{\text{max}}} \cdot 100\% \tag{4.2}
\]

where \( S_{\text{min}} \) is the minimal discharge measured and \( S_{\text{max}} \) is the maximal discharge measured. It follows that signal amplitudes lower than \( S_{\text{min}} \) will be discarded as partial discharges. To prevent the registration of noise as partial discharges, all tests were subjected to a noise suppression factor \( D_n = 10\% \). The signal dynamic \( d_s \) that results from the processing of measuring data can be calculated:

\[
d_s[dB] = 20 \cdot \log\left(\frac{S_{\text{max}}}{S_{\text{min}}}\right) \tag{4.3}
\]
where $d_s = 20\text{dB}$ in the case of noise suppression $D_n = 10\%$.

To account for the fact that unwanted signals will be interpreted as partial discharges, the effect of system noise and its statistical response was studied and is given in section 8.1.
Chapter 5
Analysis of discharges in gases

Common types of partial discharges in gases are corona discharges, surface discharges and discharges of floating parts. These three sources are analyzed in ambient air at atmospheric pressure. For surface discharges, tests were also made in sulphur hexafluoride, $SF_6$, at one atmosphere.

5.1 Corona discharges in air

Corona discharges occur at sharp points in an electric field. They occur usually at the high-voltage side, but sharp edges at earth potential may also cause corona discharges [8,16]. Two types of model were used: first, a single point-plane configuration with point diameters 40$\mu$m, 50$\mu$m, 60$\mu$m, 100$\mu$m, or 150$\mu$m, and second, a more practical type: multiple points with points diameter 50$\mu$m and 100$\mu$m, see figure 5.1.

All tests were carried out in the following two situations: the inhomogeneity at high potential, and the inhomogeneity at ground potential.

The test voltage was chosen at such a level, that the number of discharges per half voltage cycle was sufficient low to be resolved by the detector. Consequently, the tests were made at about 30% to 60% above the inception voltage. At that level corona discharges occurred at only one polarity of the a.c. test voltage.
Figure 5.1: Test arrangements for corona discharges.

<table>
<thead>
<tr>
<th>$d_1$</th>
<th>$d_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>$r$</td>
<td></td>
</tr>
<tr>
<td>40, 50, 60, 100, 150</td>
<td>30, 35, 50, 70</td>
</tr>
<tr>
<td>50, 100</td>
<td>50, 70</td>
</tr>
</tbody>
</table>

Figure 5.2: Maximum discharge magnitude $q_{\text{max}}(t)$ observed for corona discharges in air at the test voltage 4kV.

a) single point-plane configuration; point diameter 50$\mu$m, distance to plane 50mm
b) multiple point-plane configuration; point diameters 50$\mu$m, 100$\mu$m, distance to plane 50mm
5.1. CORONA DISCHARGES IN AIR

DEDUCED QUANTITIES

The test results of a point-plane configuration at 4kV voltage, with the point diameter of 50μm and the distance to the plane of 50mm will be discussed. According to [16], the following characteristics typical for corona discharges at a single point were observed: the number of discharges increases rapidly if the test voltage raised, where the inception voltage \( U_{inc}(t) \) was constant at the level of 3kV. The discharges are of equal magnitude and occur symmetrically around the voltage peak at one half cycle of the test voltage:

- in the case of a point at high voltage, discharges occur at the negative half cycle
- in the case of a point at the earth side discharges occur at the positive half cycle.

In contrast to the point-plane configuration, the discharges by multiple points were observed in both halves of the test voltage. Discharges with different magnitudes were symmetrically disposed about the voltage peaks, whereby:

- in the case of multiple points at high voltage, the larger discharges occurred at the negative half cycle
- and in the case of multiple points point at the earth side, the larger discharges occurred at the positive half cycle.

The maximum discharge magnitude \( q_{max}(t) \) of the point-plane configuration (see figure 5.2a) shows less fluctuation than that of multiple points, see figure 5.2b. The number of discharges \( N_q(t) \) of a a single point remains constant during the test, see figure 5.3a, whereas multiple points show fluctuating behaviour of \( N_q(t) \) in both halves of the voltage cycle, see figure 5.3b.

Further, an analysis of phase-position quantities \( H_{qn}(\varphi) \) and \( H_n(\varphi) \) agrees with the characteristics of the \( q_{max}(t) \) and \( N_q(t) \) quantities, see figures 5.4a and 5.4b.
Figure 5.3: Number of discharges $N_q(t)$ observed for corona discharges in air at the test voltage 4kV.

a) single point-plane configuration; point diameter $50\mu m$, distance to plane 50mm
b) multiple point-plane configuration; point diameters $50\mu m$, $100\mu m$, distance to plane 50mm
Figure 5.4: Phase-position quantities $H_{qn}(\varphi)$ and $H_n(\varphi)$ processed for corona discharges in air at the test voltage 4kV.

a) corona discharges at single point-plane configuration; point diameter 50\(\mu\)m, distance to plane 50mm

b) corona discharges at multiple point-plane configuration; point diameters 50\(\mu\)m, 100\(\mu\)m, distance to plane 50mm
CHAPTER 5. ANALYSIS OF DISCHARGES IN GASES

The different behaviour of the discharge magnitude and the discharge intensity for both models can be explained by the fact that at multiple points (for instance sharp edges) a superposition of space charges of single sharp points occur. This results in different ignition conditions for the discharges. Further, the change in discharge magnitude can be caused by changes in curvature of the points because of erosion by discharges [16].

STATISTICAL OPERATORS
The characteristics for the distributions of the phase-position quantities $H_{qn}(\varphi)$ and $H_n(\varphi)$ of both corona sources, the point-plane configuration and the multiple points configuration are given in table 5.1.

<table>
<thead>
<tr>
<th>PHASE-POSITION QUANTITIES</th>
<th>CHARACTERISTICS OF THE DISTRIBUTION</th>
<th>STATISTICAL OPERATORS</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H_{qn}(\varphi)$</td>
<td>symmetric or less asymmetric</td>
<td>Skewness is zero or small</td>
</tr>
<tr>
<td></td>
<td>flatter than the normal distribution</td>
<td>Kurtosis is negative</td>
</tr>
<tr>
<td></td>
<td>one or two tops</td>
<td>$P_e$ is small</td>
</tr>
<tr>
<td></td>
<td>little correlation between the positive half and the negative half of the voltage cycle</td>
<td>$Q$, $cc$, $mcc$ are small</td>
</tr>
<tr>
<td>$H_n(\varphi)$</td>
<td>asymmetric to the left</td>
<td>Skewness is small and positive</td>
</tr>
<tr>
<td></td>
<td>flatter than the normal distribution</td>
<td>Kurtosis is negative</td>
</tr>
<tr>
<td></td>
<td>one or two tops</td>
<td>$P_e$ is small</td>
</tr>
</tbody>
</table>

Table 5.1: Corona discharges in air

In figure 5.5a the values of statistical operators are shown for the point-plane configuration, and in figure 5.5b for the multiple points configuration.

STATISTICAL RESPONSE
In figure 5.6 the statistical response of corona discharges is given for 23 observations. The observations were made for the following
5.1. **CORONA DISCHARGES IN AIR**

**Figure 5.5:** Statistical operators processed for the $H_{pn}(\varphi)$ and $H_n(\varphi)$ distributions as shown in figure 5.4.

a) single point-plane configuration; point diameter 50\(\mu\)m, distance to plane 50mm
b) multiple point-plane configuration; point diameters 50\(\mu\)m, 100\(\mu\)m, distance to plane 50mm

**Figure 5.6:** *Statistical response* of corona discharges in air obtained for 23 tests similar to test shown in figures 5.2...5.5.
two cases: point(s) at high potential and point(s) at ground potential. Except for polarity, the same discharge patterns were observed in both cases. Therefore, the statistical response shows the same values of statistical operators $Sk$, $Ku$, $Pe$ for the positive and the negative half of the voltage cycle. The discharge factor $Q$, the cross-correlation factor $cc$ and the $mcc$ factor tell us that the discharging are asymmetrically: during only one of the half voltage cycles.

5.2 Surface discharges in air and in $SF_6$

Surface discharges occur if a stress component occurs parallel to a dielectric surface. The discharge affects the electric field so that the discharges extend beyond the region where the discharge originated [8].

In this section, the surface discharge activity will be analyzed in two gases at atmospheric pressure: air and sulphur hexafluoride gas $SF_6$. To obtain surface discharges a classical cylinder-to-plane system, made of steel or of brass was used, (see figure 5.7).

<table>
<thead>
<tr>
<th>dielectric disc thickness $d$ [mm]</th>
<th>electrode diameter $r$ [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>9</td>
</tr>
<tr>
<td>2</td>
<td>12</td>
</tr>
<tr>
<td>5</td>
<td>20</td>
</tr>
<tr>
<td>10</td>
<td></td>
</tr>
</tbody>
</table>

Figure 5.7: Test arrangements for surface discharges.

The electrode was placed on dielectric surfaces of $PE$, perspex or $PVC$. It is known that in free air surface discharges have a relatively low inception voltage, so that they occur at the average stress of 1kV/mm [8]. To obtain discharges above the detectable level of the analyzer, the tests were carried out at a the average stress of
2kV/mm. In tests in air, the required test voltage was 2kV, 4kV, 10kV, 20kV, depending on the thickness of the dielectrics surface and its permittivity. The electro-negative gas $SF_6$ at atmospheric pressure required a field strength twice as high as in the test in air.

DEDUCED QUANTITIES
The results for surface discharges in air (case A) and in $SF_6$ (case B) will be discussed. The cylinder-to-plane configuration with a 9mm brass electrode and a perspex insulation with a thickness of $d=5$mm was stressed in air at 10kV and in $SF_6$ at 20kV test voltage.

The inception voltage $U_{inc}(t)$ is in both cases characterized by strongly fluctuating behaviour (see figure 5.8).

In air as well as in $SF_6$ a significant decrease of $q_{max}(t)$ was observed during the test (see figure 5.9). Further, the value of $q_{max}(t)$ in $SF_6$ is five times lower compared to value of $q_{max}(t)$ in air.

A contrary tendency is observed in the number of discharges $N_q(t)$ (see figure 5.10): an increase of the discharge intensity occurs after 5 to 10 minutes.

These changes in maximum discharge magnitude $q_{max}(t)$ as well as in discharge intensity $N_q(t)$ can be explained as follows: because of discharge by-products (ozone, nitrous oxides) in the vicinity of the electrode, conducting acids are formed. These semi-conducting areas at the surface affect the electric field around the electrode and influence the starting point of the discharges, causing changes in the inception voltage $U_{inc}(t)$. Further, these semi-conducting areas result in a larger electrode area, causing a higher intensity of discharges.

STATISTICAL OPERATORS
Figure 5.11 shows the phase-position quantities $H_{qn}(\varphi)$ and $H_n(\varphi)$ calculated for both samples of surface discharges. The characteristics for the distributions of the phase-position quantities $H_{qn}(\varphi)$ and $H_n(\varphi)$ for both surface discharges, in air and in $SF_6$ are given in table 5.2.

In figure 5.12, the statistical operators calculated for both examples of surface discharges are shown and confirm the above observations.
Figure 5.8: Inception voltage $U_{inc}(t)$ observed for surface discharges in gases; electrode diameter 9mm, thickness of perspex insulation 5mm
a) in air at 10kV test voltage
b) in $SF_6$ at 20kV test voltage.
Figure 5.9: Maximum discharge magnitude $q_{max}(t)$ observed for surface discharges in gases; electrode diameter 9mm, thickness of perspex insulation 5mm. 

a) in air at 10kV test voltage

b) in $SF_6$ at 20kV test voltage.
Figure 5.10: Number of discharges \( N_q(t) \) observed for surface discharges in gases; electrode diameter 9mm, thickness of perspex insulation 5mm

a) in air at 10kV test voltage

b) in SF\(_6\) at 20kV test voltage.
Figure 5.11: Phase-position quantities $H_{\tau n}(\varphi)$ and $H_n(\varphi)$ processed for surface discharges in gases; electrode diameter 9mm, thickness of perspex insulation 5mm

a) in air at 10kV test voltage
b) in $SF_6$ at 20kV test voltage.
Figure 5.12: Statistical operators processed for the $H_qn(\varphi)$ and $H_n(\varphi)$ distributions as shown in figure 5.11.

a) surface discharges in air at 10kV test voltage
b) surface discharges in $SF_6$ at 20kV test voltage
## 5.2. SURFACE DISCHARGES IN AIR AND IN SF₆

<table>
<thead>
<tr>
<th>PHASE-POSITION QUANTITIES</th>
<th>CHARACTERISTICS OF THE DISTRIBUTION</th>
<th>STATISTICAL OPERATORS</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H_qn(\varphi)$</td>
<td>symmetric or less asymmetric</td>
<td>Skewness is zero or small</td>
</tr>
<tr>
<td></td>
<td>flatter than the normal distribution</td>
<td>Kurtosis is negative</td>
</tr>
<tr>
<td></td>
<td>two or three tops</td>
<td>$Pe$ is small</td>
</tr>
<tr>
<td></td>
<td>only in $SF_6$ is there little correlation between the positive half and the negative half of the voltage cycle</td>
<td>$SF_6$: $Q$, $cc$, $mcc$ are small, AIR: $Q$, $cc$, $mcc$ are high</td>
</tr>
<tr>
<td>$H_n(\varphi)$</td>
<td>asymmetric to the left</td>
<td>Skewness is positive</td>
</tr>
<tr>
<td></td>
<td>more in air than in $SF_6$, only the positive half of the voltage cycle is sharper than the normal distribution</td>
<td>Kurtosis of the positive half is positive</td>
</tr>
<tr>
<td></td>
<td>one or two tops</td>
<td>$Pe$ is small</td>
</tr>
</tbody>
</table>

### Table 5.2: Surface discharges in air and in $SF_6$

**STATISTICAL RESPONSE**

The *statistical response* for surface discharge in gases obtained from 11 tests on different dielectric materials is shown in figure 5.13. Based on these *statistical responses*, a good discrimination between surface discharges in air and those in $SF_6$ is given by the discharge factor $Q$ and the kurtosis values $Ku$ of $H_qn(\varphi)$ and $H_n(\varphi)$.

The comparison of the number of peaks $Pe$ in $H_qn(\varphi)$ and $H_n(\varphi)$ shows no significant differences between the positive and the negative half of the voltage cycle. In contrast to $Pe$, the skewness $Sk$ and kurtosis $Ku$, calculated for $H_qn(\varphi)$ and $H_n(\varphi)$ show that the values of the negative half of the voltage cycle are significantly lower than those of the positive half of the voltage cycle.

These differences might possibly be explained by the different discharging conditions during the positive half and the negative half of the voltage cycle.

To ensure that these differences were not purely a chance result, a significance test was made. For this purpose the nonparametric Kolmogorov-Smirnov two-sample test was used. This is a test to
Figure 5.13: Statistical response of surface discharges obtained for 11 tests for each gas similar to test shown in figures 5.8...5.12.

a) in air

b) in SF₆
5.3. FLOATING PARTS IN AIR

determine whether two samples originate from the same distribution. Using the hypothesis $H_0$ (the populations in question originate from the same distribution) the values of operators for the positive and the negative half of the voltage cycle were compared with a two-tailed probability level of 0.95. The results of this test are shown in table 5.3.

<table>
<thead>
<tr>
<th></th>
<th>$Sk H_{q_n}(\varphi)$</th>
<th>$Sk H_n(\varphi)$</th>
<th>$Ku H_{q_n}(\varphi)$</th>
<th>$Ku H_n(\varphi)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface discharges in AIR</td>
<td>O</td>
<td>X</td>
<td>O</td>
<td>X</td>
</tr>
<tr>
<td>Surface discharges in $SF_6$</td>
<td>O</td>
<td>X</td>
<td>O</td>
<td>X</td>
</tr>
</tbody>
</table>

X - rejects the hypothesis $H_0$
O - does not reject the hypothesis $H_0$

Table 5.3: Significance test of the difference in the values of a statistical operator between the positive half and the negative half of the voltage cycle for surface discharges in gases

This table illustrates that the hypothesis $H_0$ was rejected in the majority of the cases. Similar significance tests for discharges in liquids and solid materials have shown that in no case was the hypothesis $H_0$ rejected. This means that the differences between the positive half and the negative half of the voltage cycle are only significant for surface discharges in gases. Thus this characteristic can be used to discriminate between surface discharges in gases and other discharge sources as well.

5.3 Floating parts in air

Sometimes, if badly earthed components or floating parts occur in or near the high-voltage circuit, these defects may cause disturbances which are detected as discharge patterns [8,16]. The discharges occur in an air gap between two conducting parts when a potential difference is caused by capacitive coupling. These induced discharges are
sometimes difficult to distinguish from real discharges. They are, for instance, caused by:

- metallic parts lying on the ground in the vicinity of a high-voltage circuit
- a loose connection of an earthed screen inside a test object: [80].

To analyze these discharges, an ungrounded metallic plate was placed at 50cm distance from the high-voltage terminal of a test object. The air gap between the plate and the earth was varied between 2mm and 0.1mm (see figure 5.14). As a test object, a specimen was chosen with a capacitance $C_s=4\mu\text{F}$, that was discharge free up to 30kV.

<table>
<thead>
<tr>
<th>high voltage distance $d$ [mm]</th>
<th>air gap distance $x$ [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image.png" alt="Diagram" /></td>
<td>50</td>
</tr>
<tr>
<td></td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>1.5</td>
</tr>
<tr>
<td></td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>0.1</td>
</tr>
</tbody>
</table>

Figure 5.14: Test arrangements for floating parts.

Before the tests were started the detection circuit was calibrated. The test voltage was varied between 4kV up to 20kV, depending on the air gap distance.

The characteristic features of these discharge patterns [16] were observed. Discharges of more or less equal amplitude were observed on both halves of the voltage cycle in advance of the voltage peaks. At a voltage of 4kV the discharges remain stationary; at higher voltages they start to move between the tops of the test waveform.

DEDUCED QUANTITIES

As an example of discharges by floating parts, the results of the test arrangement at 10kV test voltage described above will be analyzed
here. In figure 5.15, the inception voltage \( U_{inc}(t) \) shows that the response is unaffected by time [16]. The same observations were made for the maximum discharge magnitude \( q_{max}(t) \) and the number of discharges \( N_q(t) \) (see figures 5.16 and 5.17). However, in some of other tests, a temporary disappearance of discharges was observed [16].

**Figure 5.15:** Inception voltage \( U_{inc}(t) \) observed for a floating part at a test voltage of 10kV.

**Figure 5.16:** Maximum discharge magnitude \( q_{max}(t) \) observed for a floating part at a test voltage of 10kV.

**STATISTICAL OPERATORS**

As the discharges of the same amplitude and are more or less equally spaced between the voltage peaks, characteristic shapes of the distribution \( H_{qn}(\varphi) \) and \( H_n(\varphi) \) are given (see figure 5.18). The characteristics for these distributions are given in table 5.4.
Figure 5.17: Number of discharges $N_q(t)$ observed for a floating part at a test voltage of 10kV.

Figure 5.18: Phase-position quantities $H_{q_n}(\varphi)$ and $H_n(\varphi)$ processed for a floating part at a test voltage of 10kV.
CONCLUSIONS

<table>
<thead>
<tr>
<th>PHASE-POSITION QUANTITIES</th>
<th>CHARACTERISTICS OF THE DISTRIBUTION</th>
<th>STATISTICAL OPERATORS</th>
</tr>
</thead>
<tbody>
<tr>
<td>( H_{qn}(\varphi) )</td>
<td>symmetric</td>
<td>Skewness is zero</td>
</tr>
<tr>
<td></td>
<td>flatter than the normal distribution</td>
<td>Kurtosis is negative</td>
</tr>
<tr>
<td></td>
<td>several tops</td>
<td>( Pe ) is high</td>
</tr>
<tr>
<td></td>
<td>high correlation between the positive half and the negative half of the voltage cycle</td>
<td>( Q, \text{ cc, mcc} ) are high</td>
</tr>
<tr>
<td>( H_n(\varphi) )</td>
<td>asymmetric to the left</td>
<td>Skewness is small and positive</td>
</tr>
<tr>
<td></td>
<td>flatter than the normal distribution</td>
<td>Kurtosis is negative</td>
</tr>
<tr>
<td></td>
<td>several tops</td>
<td>( Pe ) is high</td>
</tr>
</tbody>
</table>

Table 5.4: Floating parts in air

In figure 5.19 the statistical operators calculated for this example of a floating part are given, which confirms these characteristic features.

![Figure 5.19: Statistical operators processed for the \( H_{qn}(\varphi) \) and \( H_n(\varphi) \) distributions as shown in figure 5.18.]

STATISTICAL RESPONSE

The statistical response of 15 tests made for floating parts is presented in figure 5.20. The comparison of statistical operators, skewness \( Sk \), kurtosis \( Ku \) and the number of peaks \( Pe \) calculated for \( H_{qn}(\varphi) \) and \( H_n(\varphi) \) show that there are no significant differences between the values of the positive half and the negative half of the voltage cycle.
Figure 5.20: Statistical response of floating part in air for 15 tests similar to test shown in figures 5.15...5.19.

5.4 Conclusions on partial discharges in gases

1. Conclusions related to time dependency of deduced quantities:
   - Corona as well as floating parts are characterized by a less fluctuating behaviour of $U_{inc}(t)$, $q_{max}(t)$ and $N_q(t)$.
   - Surface discharges are characterized by a more fluctuating behaviour pattern of $U_{inc}(t)$, $q_{max}(t)$ as well as an increasing number of discharges $N_q(t)$.

2. Conclusions related to statistical response: table 5.5 shows the discriminating features for discharges in gases obtained by means of the statistical response of these defects.
### 5.4. CONCLUSIONS ON PARTIAL DISCHARGES IN GASES

<table>
<thead>
<tr>
<th>DISCRIMINATING FEATURE</th>
<th>CORONA IN AIR</th>
<th>SURFACE DISCHARGES IN AIR AND IN SF&lt;sub&gt;6&lt;/sub&gt;</th>
<th>FLOATING PARTS IN AIR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Skewness of $H_{qn}(\varphi)$ is negative</td>
<td>YES</td>
<td>NO</td>
<td>NO</td>
</tr>
<tr>
<td>$Q$, $cc$ and $mcc$ are small</td>
<td>YES</td>
<td>NO</td>
<td>NO</td>
</tr>
<tr>
<td>Skewness of $H_n(\varphi)$ is high and positive</td>
<td>NO</td>
<td>YES</td>
<td>NO</td>
</tr>
<tr>
<td>Kurtosis of $H_n(\varphi)$ is different for the positive half and the negative half of the voltage cycle</td>
<td>NO</td>
<td>YES</td>
<td>NO</td>
</tr>
<tr>
<td>Number of peaks of $H_{qn}(\varphi)$ and $H_n(\varphi)$ is high</td>
<td>NO</td>
<td>NO</td>
<td>YES</td>
</tr>
</tbody>
</table>

Table 5.5: Discharge in gases
Chapter 6
Analysis of discharges in liquids

Insulating liquids in high-voltage systems are usually synthetic or mineral oils. These are in particular silicones, used in the majority of small transformers and mineral oils used above all in power transformers. In highly purified insulating liquids, where all interfering effects are prevented, partial discharges do not occur. Here, high electric breakdown strengths can be reached: the intrinsic breakdown strength which occurs at field strengths between 100kV/mm and to 250kV/mm [81]. However, in the liquids used in actual engineering practice impurities occur; gaseous bubbles or microscopic conducting particles and partial discharges can be initiated, causing a much lower breakdown strength, in the order of 30kV/mm [82]. Further, inhomogeneities such as sharp points or dielectrics with field components parallel to the surface can cause partial discharges.

To analyze these kinds of discharges patterns in liquids, two typical discharge arrangements were analyzed: a point-plane configuration and a cylinder-to-plane configuration. For this purpose, the test arrangements discussed in chapter 5, see figures 5.1 and 5.7 were tested, but they were immersed in moist transformer mineral oil, Diala C (Shell), with a viscosity of 20cSt, containing ca. 100ppm water. Because of the disappearance of discharges at lower values of overvoltage, the test voltage was chosen to be at 60% above inception voltage.
6.1 Corona discharges in oil

Test results were obtained with a point-plane configuration, at 50kV test voltage, using a needle with a point diameter of 50μm having a distance to the plane of 50mm. Compared to the same test arrangement in air, where an inception voltage of 2.5kV was required, the inception voltage in oil was 32kV. In accordance with [16], discharges appeared several seconds after the voltage was applied. The discharges occurred on both half cycles around the voltage peaks, but were not symmetrically disposed around the peaks, in contrast to [16].

DEDUCED QUANTITIES
The time behaviour of \( U_{inc}(t) \) is shown in figure 6.1. Strong changes in the inception voltage \( U_{inc}(t) \) as well as in the maximum discharge magnitude \( q_{max}(t) \) and in the number of discharges \( N_q(t) \) were characteristic for all tests (see figures 6.2 and 6.3). In contrast to the gaseous discharge presented in chapter 5, there was a low correlation between the variations in these three quantities.

![Figure 6.1: Inception voltage \( U_{inc}(t) \) observed for corona discharges in oil at the test voltage of 50kV; point diameter 50μm, distance to plane 50mm.](image)

The discharge mechanisms in liquids depend on several factors. There is a strong dependency between the field strength and the conductivity of the liquids: from 5kV/mm onward the resistance of liquids always decreases. Consequently, the liquid is no longer an insulator, although the phenomenon has nothing to do with breakdown or pre-breakdown [83]. The evolution of discharges in liquids has been
Figure 6.2: Maximum discharge magnitude $q_{\text{max}}(t)$ observed for corona discharges in oil at the test voltage of 50kV; point diameter 50μm, distance to plane 50mm.

Figure 6.3: Number of discharges $N_q(t)$ observed for corona discharges in oil at the test voltage of 50kV; point diameter 50μm, distance to plane 50mm.
shown to be a complex electro-hydrodynamical problem [84]. The characteristic elements of electrical breakdown in liquids are the formation of low density channels, the charge mobility being strongly dependent on the electric field, and its polarity; moreover the viscosity, the temperature and the moisture of the liquid [85]. In consequence, discharges in liquids are not necessarily permanent, their occurrence depends on many factors and has a complex character.

![Graph](image)

Figure 6.4: Phase-position quantities $H_{qn}(\varphi)$ and $H_n(\varphi)$ processed for corona discharges in oil at the test voltage of 50kV; point diameter 50\(\mu\)m, distance to plane 50mm.

**STATISTICAL OPERATORS**

The phase-position quantities $H_{qn}(\varphi)$ and $H_n(\varphi)$, calculated for the point-plane configuration in oil, are given in figure 6.5. In table 6.1, the characteristic features for these distributions are given. The statistical operators calculated for the above-mentioned distributions are shown in figure 6.5.

**STATISTICAL RESPONSE**

In figure 6.6, the statistical response of 10 tests obtained by corona in oil is shown. The significant difference between the kurtosis values $Ku$ calculated for the $H^+_n(\varphi)$ and $H^-_n(\varphi)$ distributions is characteristic. All other operators were characterized by approximately equal values for both halves of the voltage cycle. Further, the kurtosis values of the $H_{qn}(\varphi)$ and $H^+_n(\varphi)$ distributions show a significantly high dispersion compared to corona discharges in air (see figure 5.10)
### 6.1. Corona Discharges in Oil

<table>
<thead>
<tr>
<th>PHASE-POSITION QUANTITIES</th>
<th>CHARACTERISTICS OF THE DISTRIBUTION</th>
<th>STATISTICAL OPERATORS</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H_{qn}(\varphi)$</td>
<td>asymmetric to the left</td>
<td>Skewness is positive</td>
</tr>
<tr>
<td></td>
<td>does not deviate from the normal distribution</td>
<td>Kurtosis is zero or small</td>
</tr>
<tr>
<td></td>
<td>several tops</td>
<td>$Pe$ is high</td>
</tr>
<tr>
<td></td>
<td>high correlation between the positive half and the negative half of the voltage cycle</td>
<td>$Q$, $cc$, $mcc$ are high</td>
</tr>
<tr>
<td>$H_n(\varphi)$</td>
<td>asymmetric to the left</td>
<td>Skewness is positive</td>
</tr>
<tr>
<td></td>
<td>the positive half of the voltage cycle is sharper than the normal distribution</td>
<td>Kurtosis is positive of the positive half of the voltage cycle</td>
</tr>
<tr>
<td></td>
<td>several tops</td>
<td>$Pe$ is high</td>
</tr>
</tbody>
</table>

**Table 6.1:** Corona discharges in oil

![Diagram](image)

**Figure 6.5:** Statistical operators processed for the $H_{qn}(\varphi)$ and $H_n(\varphi)$ distributions as shown in figure 6.4.
Figure 6.6: Statistical response of corona discharges in oil obtained for 10 tests similar to test shown in figures 6.1...6.5.

6.2 Surface discharges in oil

Surface discharges along solid dielectric surfaces in transformer oil were produced by means of the experimental arrangements described in section 5.2, see figure 5.7. The tests were carried out at a field strength of 3.5kV/mm. Depending on the thickness of the disc, the applied test voltage was 4kV, 8kV, 18kV or 35kV. During the tests fluctuating discharge patterns were observed: many small discharges and few large discharges were measured. The large discharges slowly disappeared during the test. Similar to the behaviour of corona in oil (see section 6.1) a temporary disappearance of discharges was observed.

Figure 6.7: Inception voltage \( U_{\text{inc}}(t) \) observed for surface discharges in oil at a test voltage of 35kV; electrode diameter 9mm, thickness of perspex insulation 5mm.
6.2. SURFACE DISCHARGES IN OIL

Figure 6.8: Maximum discharge magnitude $q_{max}(t)$ observed for surface discharges in oil at a test voltage of 35kV; electrode diameter 9mm, thickness of perspex insulation 5mm.

Figure 6.9: Number of discharges $N_q(t)$ observed for surface discharges in oil at a test voltage of 35kV; electrode diameter 9mm, thickness of perspex insulation 5mm.
DEDUCED QUANTITIES
The observation presented here was made on a cylinder-to-plane configuration: a 9mm brass electrode on a perspex disc with a thickness of 10mm was tested at a 35kV. In figures 6.7, 6.8 and 6.9 the quantities: inception voltage $U_{inc}(t)$, maximum discharge magnitude $q_{max}(t)$ and number of discharges $N_q(t)$ are given. These quantities were characterized by the weaker changes observed in the same test arrangements in air and in $SF_6$. Further, the characteristics of surface discharges in gases: the decreasing $q_{max}(t)$ as well as the increasing $N_q(t)$ during the test, were not observed in surface discharges in oil.

STATISTICAL OPERATORS

Figure 6.10: Phase-position quantities $H_{qn}(\varphi)$ and $H_n(\varphi)$ processed for surface discharges in oil at a test voltage of 35kV; electrode diameter 9mm, thickness of perspex insulation 5mm.

Figure 6.10 shows the phase-position quantities $H_{qn}(\varphi)$ and $H_n(\varphi)$ calculated for the experimental arrangements discussed. The characteristics of these distributions are given in table 6.2.
The statistical operators calculated for the above-mentioned distributions are shown in figure 6.11.

STATISTICAL RESPONSE
The statistical response of 10 tests is shown in figure 6.12. No operators show a significant difference between the positive and the negative half of the voltage cycle. Especially, no difference occurs between the kurtosis $Ku$ of $H_n^+(\varphi)$ and $H_n^-(\varphi)$. This is in contrast
### Table 6.2: Surface discharges in oil

<table>
<thead>
<tr>
<th>PHASE-POSITION QUANTITIES</th>
<th>CHARACTERISTICS OF THE DISTRIBUTION</th>
<th>STATISTICAL OPERATORS</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H_{q_0}(\varphi)$</td>
<td>less asymmetric to the left</td>
<td>Skewness is small and positive</td>
</tr>
<tr>
<td></td>
<td>flatter than the normal distribution</td>
<td>Kurtosis is negative</td>
</tr>
<tr>
<td></td>
<td>several tops</td>
<td>$P_e$ is high</td>
</tr>
<tr>
<td></td>
<td>high correlation between the positive half and the negative half of the voltage cycle</td>
<td>$Q$, $cc$, $mcc$ are high</td>
</tr>
<tr>
<td>$H_n(\varphi)$</td>
<td>the positive half of the voltage cycle is asymmetric to the right</td>
<td>Skewness of the positive half is negative</td>
</tr>
<tr>
<td></td>
<td>only the negative half of the voltage cycle is flatter than the normal distribution</td>
<td>Kurtosis of the negative half is negative</td>
</tr>
<tr>
<td></td>
<td>several tops</td>
<td>$P_e$ is high</td>
</tr>
</tbody>
</table>

**Figure 6.11:** Statistical operators processed for the $H_{q_0}(\varphi)$ and $H_n(\varphi)$ distributions as shown in figure 6.10.
to the surface discharges in gases. Further, a significantly higher dispersion is found for the kurtosis values $Ku$ of $H_{qn}(\varphi)$ and $H_n(\varphi)$, similar to the dispersion of corona in oil.

### 6.3 Conclusions on discharges in liquids

1. Conclusions related to the time dependency of deduced quantities:

   - Corona and surface discharges in oil are characterized by the strongly fluctuating behaviour of $U_{inc}(t)$, $q_{max}(t)$ and $N_q(t)$, resulting in the temporary disappearance of discharges.
   - Using $U_{inc}(t)$, $q_{max}(t)$ and $N_q(t)$, discrimination between corona and surface discharges was not possible.

2. Conclusions related to statistical response:

   Table 6.3 shows the discriminating features for discharges in oil obtained by means of statistical response of these defects.

   The comparison of the statistical response of corona in oil and in air respectively gives the following differences:

   - Corona in oil is characterized by positive values of skewness $Sk$ on $H_{qn}(\varphi)$, whereas corona in air has zero or negative values of $Sk$ on $H_{qn}(\varphi)$. 

\[ \text{Figure 6.12: Statistical response of surface discharges in oil obtained for 10 tests similar to test shown in figures 6.7...6.11.} \]
<table>
<thead>
<tr>
<th>DISCRIMINATING FEATURE</th>
<th>CORONA IN OIL</th>
<th>SURFACE DISCHARGES IN OIL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Skewness of $H_{qn}(\varphi)$ is positive and high</td>
<td>YES</td>
<td>NO</td>
</tr>
<tr>
<td>$Q$, $cc$ and $mcc$ are high</td>
<td>NO</td>
<td>YES</td>
</tr>
<tr>
<td>Skewness of $H_n(\varphi)$ is different for the positive half and the negative half of the voltage cycle</td>
<td>NO</td>
<td>YES</td>
</tr>
<tr>
<td>Kurtosis of $H_n(\varphi)$ is different for the positive half and the negative half of the voltage cycle</td>
<td>YES</td>
<td>NO</td>
</tr>
</tbody>
</table>

Table 6.3: Discharge in liquids

- Corona in oil is characterized by higher values of kurtosis $Ku$ on $H_{qn}(\varphi)$, whereas corona in air has high negative values of $Ku$ on $H_{qn}(\varphi)$.

- A higher number of peaks $Pe$ for $H_{qn}(\varphi)$ and $H_n(\varphi)$ distribution discriminates corona in oil from corona in air, the same is true for surface discharges.

- Corona in air is characterized by zero or relatively low values of the discharge factor $Q$, the cross-correlation $cc$ and the $mcc$ factor.

The comparison of the statistical response of surface discharges in oil and these in gases provides the following conclusions which enable discrimination between these discharges:

- Surface discharges in oil were characterized by much lower values of skewness $Sk$ on $H_n(\varphi)$ than those of discharges in gases.

- Surface discharges in oil show a higher number of peaks $Pe$ for the $H_{qn}(\varphi)$ and $H_n(\varphi)$ distributions than in gases.
Chapter 7
Analysis of discharges in solid materials

The technologically most important sources of partial discharges are cavities in solid dielectric systems. Detection of such defects is one of the most frequent applications of partial discharge analysis. The relationship between the discharge patterns and the size, the shape, and the position of the cavity within a solid dielectric is very important for the assess of insulating systems.

Equally important is electrical treeing in solid dielectrics. The electrical trees may be initiated by conductive parts like small metal inclusions, but they can also be initiated by cavities. At practical field strengths up to 5-10 kV/mm, the initiation of electrical trees can take hours, weeks or even years. After the treeing has been initiated, the growth of the tree is usually very destructive to the insulation and breakdown may take place after several minutes. Therefore the monitoring of electrical treeing plays an important role in routine tests on insulating systems.

To investigate whether typical sources of discharges in solids can be recognized by a specific discharge pattern, the following series of artificial defects were prepared:

- single cavity (square, flat, narrow)
- multiple cavities
- electrode-bounded versus dielectric-bounded cavity
- treeing initiated by a conductor
• treeing initiated by a cavity.

![Figure 7.1](image.png)

**Figure 7.1:** Electrode configuration of samples with cavities.

Each series consisted of perspex, PE and PVC samples containing a cylindrical cavity with specific dimension. To account for the fact that cavities in actual dielectrics are not always regularly shaped with smooth surface, cavities with rough and irregular surfaces were studied as well. During the test the specimens were placed centrally-symmetrically in a homogeneous field between two Rogowski electrodes, see figure 7.1. The electrodes were partly covered with high viscosity oil and partly embedded in polyester in order to prevent unwanted discharges at the electrode edges. Mechanical pressure on the electrodes ensured good contact with the dielectric. The set-up was discharge free up to 9kV/mm field strength, which made the study of the discharges in the cavity possible.

### 7.1 Single cavity

The experiments were carried out using three series of specimens, containing a square, a flat and a narrow cylindrical cavity respectively, see figure 7.2. The cavities were located in the middle of the
dielectric. The test voltage was chosen to be 30% to 60% over the inception voltage in order to prevent the self-extinction of discharges during the test time.

<table>
<thead>
<tr>
<th>cavity</th>
<th>diameter d [mm] / height h [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>![Diagram 1]</td>
<td>1 / 1; 1.2 / 1;</td>
</tr>
<tr>
<td>![Diagram 2]</td>
<td>1 / 1; 1 / 0.7;</td>
</tr>
<tr>
<td>![Diagram 3]</td>
<td>1 / 1; 2 / 2;</td>
</tr>
<tr>
<td>![Diagram 4]</td>
<td>2 / 1; 3 / 1; 5 / 1; 10 / 1; 10 / 0.1;</td>
</tr>
<tr>
<td>![Diagram 5]</td>
<td>2 / 0.5; 5 / 0.5; 10 / 1; 10 / 0.1;</td>
</tr>
<tr>
<td>![Diagram 6]</td>
<td>2 / 1; 5 / 1;</td>
</tr>
<tr>
<td>![Diagram 7]</td>
<td>1 / 5; 1 / 10;</td>
</tr>
<tr>
<td>![Diagram 8]</td>
<td>1 / 2.5; 1 / 5; 1 / 10;</td>
</tr>
<tr>
<td>![Diagram 9]</td>
<td>1 / 5; 1 / 10;</td>
</tr>
</tbody>
</table>

Figure 7.2: Test samples for cavity discharges.

**DEDUCED QUANTITIES**

The results of the tests on the following three categories of cavities in perspex are discussed here. The geometric shapes, the field strength at discharge inception and the field strength during the test are given in table 7.1 [88].

<table>
<thead>
<tr>
<th>CAVITY TYPE</th>
<th>DIAMETER</th>
<th>HEIGHT</th>
<th>DISCHARGE IGNITION</th>
<th>TESTED AT</th>
</tr>
</thead>
<tbody>
<tr>
<td>SQUARE</td>
<td>1mm</td>
<td>1mm</td>
<td>3,3kV/mm</td>
<td>4,4kV/mm</td>
</tr>
<tr>
<td>FLAT</td>
<td>5mm</td>
<td>1mm</td>
<td>2,3kV/mm</td>
<td>3,3kV/mm</td>
</tr>
<tr>
<td>NARROW</td>
<td>1mm</td>
<td>5mm</td>
<td>2,8kV/mm</td>
<td>4,4kV/mm</td>
</tr>
</tbody>
</table>

Table 7.1: Cavities geometry and their test conditions
The behaviour of the inception voltage $U_{inc}(t)$ shows (for all three cavities) either an increase within the first 5 to 10 minutes of the test, or the discharges even extinguishes, see figure 7.3.

Also, the behaviour of $q_{max}(t)$ in figure 7.4 shows qualitative differences between the samples. The characteristics are:

- temporary extinction of discharges in the square cavity
- a decrease in the discharge level in the flat cavity
- a sudden drop in the discharge magnitude in the narrow cavity.

In figure 7.5 the numbers of discharges $N_q(t)$ are given. The number of discharges $N_q(t)$ in the flat cavity was significantly higher, although the field strength in the dielectrics with the square and narrow cavities was higher than that with the flat cavities, see table 7.1.

To explain this characteristic, the field strength in the cavities (at the onset of the discharges) was studied. In the flat cavity, the field strength was about $\varepsilon E$, where $E$ is the field strength in the dielectric. In a square cavity, the field strength is about equal to $(3\varepsilon/(1+2\varepsilon))\cdot E$. The field strength in a narrow cavity (cavity in the direction of the field) equaled the field strength in the dielectric. It results for flat cavities in the highest field strength of 11kV/mm, for a square cavity in a field strength of 5.7kV/mm, and the field strength in the narrow cavity was almost the same as in the dielectric, 4.4kV/mm. The changes in the time behaviour of the quantities could well be explained by the creation of (semi)conducting layers at the surface of the cavity. These layers are caused by the formation of acids in the discharge process [57]. The (semi)conducting surfaces led to a changed electric field in the cavity, the voltage over the cavity decreases and the inception voltage rises accordingly. Surface conductivity measurements on the cavity surface confirmed a significant rise in conductivity (from below 2x10S to 1.3x10S), [86,87]. In consequence, a higher inception voltage $U_{inc}(t)$ was attended by a decrease in the discharge intensity $N_q(t)$ and by a decrease in the maximum discharge magnitude $q_{max}(t)$.

In cavities with large surfaces (flat or even a square cavity) discharges may occur at different sites at the surface. As the voltage is raised
Figure 7.3: Inception voltage $U_{inc}(t)$ observed for discharges in cylindrical cavities in perspex

a) square cavity: 1mm x 1mm, tested at 4.4kV/mm field strength
b) flat cavity: 5mm x 1mm, tested at 3.3kV/mm field strength
c) narrow cavity: 1mm x 5mm, tested at 4.4kV/mm field strength.
Figure 7.4: Maximum discharge magnitude $q_{max}(t)$ observed for discharges in cylindrical cavities in perspex
a) square cavity: 1mm x 1mm, tested at 4,4kV/mm field strength
b) flat cavity: 5mm x 1mm, tested at 3,3kV/mm field strength
c) narrow cavity: 1mm x 5mm, tested at 4,4kV/mm field strength.
Figure 7.5: Number of discharges $N_q(t)$ observed for discharges in cylindrical cavities in perspex

a) square cavity: 1mm x 1mm, tested at 4,4kV/mm field strength
b) flat cavity: 5mm x 1mm, tested at 3,3kV/mm field strength
c) narrow cavity: 1mm x 5mm, tested at 4,4kV/mm field strength.
Figure 7.6: Phase-position quantities $H_n(\varphi)$ and $H_q(\varphi)$ processed for discharges in cylindrical cavities in perspex

a) square cavity: 1mm x 1mm, tested at 4.4kV/mm field strength
b) flat cavity: 5mm x 1mm, tested at 3.3kV/mm field strength
c) narrow cavity: 1mm x 5mm, tested at 4.4kV/mm field strength.
during the half cycle, larger discharges occur, followed by smaller discharges in advance of the voltage peaks. In these cavities, the (semi)conducting layers do not cover the entire surface of the cavity, resulting in a decrease of discharge magnitudes, in contrast to smaller cavities where extinction occurs.

**STATISTICAL OPERATORS**

Figure 7.6 shows the phase-position quantities $H_{qn}(\varphi)$ and $H_{n}(\varphi)$, calculated for three types of cavities. The characteristics for these distributions for these three cases of cavities are given in table 7.2.

<table>
<thead>
<tr>
<th>PHASE-POSITION QUANTITIES</th>
<th>CHARACTERISTICS OF THE DISTRIBUTION</th>
<th>STATISTICAL OPERATORS</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H_{qn}(\varphi)$</td>
<td>asymmetric to the left only SQUARE and FLAT CAVITY</td>
<td>Skewness is positive</td>
</tr>
<tr>
<td></td>
<td>flatter than the normal distribution</td>
<td>Kurtosis is negative</td>
</tr>
<tr>
<td></td>
<td>one or two tops</td>
<td>$Pe$ is small</td>
</tr>
<tr>
<td></td>
<td>high correlation between the positive half and the negative half of the voltage cycle</td>
<td>$Q$, $cc$, $mcc$ are high</td>
</tr>
<tr>
<td>$H_{n}(\varphi)$</td>
<td>asymmetric to the left only SQUARE and FLAT CAVITY</td>
<td>Skewness is positive</td>
</tr>
<tr>
<td></td>
<td>much sharper than the the normal distribution</td>
<td>Kurtosis is positive</td>
</tr>
<tr>
<td></td>
<td>only SQUARE and FLAT CAVITY</td>
<td>$Pe$ is small</td>
</tr>
<tr>
<td></td>
<td>one or two tops</td>
<td></td>
</tr>
</tbody>
</table>

Table 7.2: Cavity discharges

In figure 7.7, the values of the statistical operators are shown for three types of cavities in perspex.

**STATISTICAL RESPONSE**

The *statistical responses* of 14 tests for each of the three types of single cavities are given in figure 7.8. There appears to be no difference between the positive and the negative half of the voltage cycle. The following characteristics were defined to describe the cavities and to distinguish cavities with different shapes, see table 7.3.
Figure 7.7: Statistical operators processed for the $H_{\tau \nu}(\varphi)$ and $H_{\nu}(\varphi)$ distributions as shown in figure 7.6.

a) square cavity: 1mm x 1mm, tested at 4.4kV/mm field strength
b) flat cavity: 5mm x 1mm, tested at 3.3kV/mm field strength
c) narrow cavity: 1mm x 5mm, tested at 4.4kV/mm field strength.
**Figure 7.8:** *Statistical response* of discharges in a cylindrical cavity obtained for 14 tests for each of the three types cavities similar to test shown in figures 7.3...7.7.  

a) square cavity  
b) flat cavity  
c) narrow cavity.
Table 7.3: Discharges in a single cavity

<table>
<thead>
<tr>
<th>DISCRIMINATING FEATURE</th>
<th>SQUARE CAVITY</th>
<th>FLAT CAVITY</th>
<th>NARROW CAVITY</th>
</tr>
</thead>
<tbody>
<tr>
<td>Skewness of $H_n(\varphi)$ is zero or small negative</td>
<td>NO</td>
<td>NO</td>
<td>YES</td>
</tr>
<tr>
<td>Skewness of $H_n(\varphi)$ is positive and high</td>
<td>YES</td>
<td>YES</td>
<td>NO</td>
</tr>
<tr>
<td>Kurtosis of $H_n(\varphi)$ is positive</td>
<td>NO</td>
<td>YES</td>
<td>YES</td>
</tr>
</tbody>
</table>

7.2 Dielectric-bounded and electrode-bounded cavity

If cavity discharges are recognized, it is often important to know the position of the defect within the dielectric. Generally, a distinction can be made between two situations: the cavity is surrounded by the dielectric or the cavity is located between the dielectric and the conductor. To date, several authors [8,16] have proposed the oscillographic means to distinguish between these cases. The conventional oscillographic observation, however, often leaves room for considerable doubt.

To find a discriminator for these two locations, samples with a flat cavity adjuncts to the conductor and a flat cavity within dielectric were tested, see figure 7.9. The lower electrode in the test arrangement in figure 7.1 was at high voltage. The electrode-bounded side of the cavity was connected to the high voltage electrode.

Observe that only one type of cavity was studied: a flat one.

The test samples were subjected to a voltage test at 20% above the discharge inception voltage. This test level was chosen, as (self) extinction usually in electrode-bounded cavities occurs at lower values [86].

DEDUCED QUANTITIES

Cavities with a diameter of 10mm, a high of 1mm and the surface roughness of 0.05μm were subjected to 2kV/mm field strength in the dielectric.

Figure 7.10 shows examples of the inception voltage $U_{inc}(t)$ of a
<table>
<thead>
<tr>
<th>cavity</th>
<th>diameter d[mm] / height h [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1.png" alt="cavity1" /></td>
<td>3 / 1; 5 / 1; 10 / 1; 10 / 0.1;</td>
</tr>
<tr>
<td><img src="image2.png" alt="cavity2" /></td>
<td>2 / 0.5; 5 / 0.5; 10 / 1;</td>
</tr>
</tbody>
</table>
| ![cavity3](image3.png) | (1) 10 / 1; 10 / 1;  
                      (2) 2 / 0.5; 5 / 1; |

- surface with roughness 0.05 [μm]  
- surface with roughness 3.2 [μm]

**Figure 7.9:** Test samples for discharges in dielectric- and electrode-bounded cavity.

dielectric-bounded and electrode-bounded cavity. Similarly to the cavities in section 7.1, \(U_{inc}(t)\) is characterized by an increase during the first 5 minutes. The difference in the change of inception voltage in the positive half and the negative half of the voltage cycle for the electrode-bounded cavity is interesting. In the negative half of the voltage cycle, extinction occurs often whilst in the positive half of the voltage cycle, a stable value of the inception voltage is reached after 5 minutes.

The behaviour of \(q_{max}(t)\) is given for both cases in figure 7.11. The dielectric-bounded cavity is characterized by equal discharge magnitudes in both halves of the voltage cycle. The electrode-bounded cavity is characterized by a significant difference between the positive half and the negative half of the voltage cycle [86,89].

In figure 7.12, the number of discharges \(N_q(t)\) is shown. Similar to the dielectric-bounded cavities discussed in section 7.1, a decrease of the number \(N_q(t)\) is visible. The electrode-bounded cavity is, however, characterized by less similarity in both halves of the voltage cycle.

The asymmetry could be explained as follows: during the positive
Figure 7.10: Inception voltage $U_{inc}(t)$ observed for discharges in a cylindrical cavity in PVC

(a) dielectric-bounded cavity: 10mm x 1mm, tested at 2kV/mm field strength
(b) electrode-bounded cavity: 10mm x 1mm, tested at 2kV/mm field strength.
Figure 7.11: Maximum discharge magnitude $q_{\text{max}}(t)$ observed for discharges in a cylindrical cavities in PVC

a) dielectric-bounded cavity: 10mm x 1mm, tested at 2kV/mm field strength
b) electrode-bounded cavity: 10mm x 1mm, tested at 2kV/mm field strength.
**Figure 7.12:** Number of discharges $N_q(t)$ observed for discharges in a cylindrical cavity in PVC

a) dielectric-bounded cavity: 10mm x 1mm, tested at 2kV/mm field strength

b) electrode-bounded cavity: 10mm x 1mm, tested at 2kV/mm field strength.
half, the remnant charge on the surface the dielectric result in a larger supply of initiating electrons. In the negative half cycle, initiating electrons have to be liberated from the electrode or supplied by natural background radiation [87].

Figure 7.13: Phase-position quantities $H_{qn}(\varphi)$ and $H_n(\varphi)$ processed for discharges in a cylindrical cavity in PVC
a) dielectric-bounded cavity: 10mm x 1mm, tested at 2kV/mm field strength
b) electrode-bounded cavity: 10mm x 1mm, tested at 2kV/mm field strength.

**STATISTICAL OPERATORS**
The $H_{qn}(\varphi)$ and $H_n(\varphi)$ distributions for these examples are shown in figure 7.13. The characteristics for these distributions for both dielectric-bounded and electrode-bounded cavities are given in table 7.4.
In figure 7.14, the statistical operators for these two cavity locations are shown.
<table>
<thead>
<tr>
<th>PHASE-POSITION QUANTITIES</th>
<th>CHARACTERISTICS OF THE DISTRIBUTION</th>
<th>STATISTICAL OPERATORS</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H_{qn}(\varphi)$</td>
<td>asymmetric to the left</td>
<td>Skewness is positive</td>
</tr>
<tr>
<td></td>
<td>the negative half of the voltage cycle is flatter than the normal distribution</td>
<td>Kurtosis of the negative half is negative</td>
</tr>
<tr>
<td></td>
<td>one or two tops</td>
<td>$Pe$ is small</td>
</tr>
<tr>
<td></td>
<td>little correlation between the positive half and the negative half of the voltage cycle only ELECTRODE-BOUNDED CAVITY</td>
<td>$Q$, $mcc$ are small</td>
</tr>
<tr>
<td>$H_n(\varphi)$</td>
<td>more than $H_{qn}(\varphi)$</td>
<td>Skewness is positive and higher than this of $H_{qn}(\varphi)$</td>
</tr>
<tr>
<td></td>
<td>only ELECTRODE-BOUNDED CAVITY</td>
<td></td>
</tr>
<tr>
<td></td>
<td>sharper than the normal distribution</td>
<td>Kurtosis is positive</td>
</tr>
<tr>
<td></td>
<td>one or two tops</td>
<td>$Pe$ is small</td>
</tr>
</tbody>
</table>

Table 7.4: Dielectric-bounded and electrode-bounded cavity
Figure 7.14: Statistical operators processed for the $H_{mn}(\varphi)$ and $H_n(\varphi)$ distributions as shown in figure 7.13.

a) dielectric-bounded cavity: 10mm x 1mm, tested at 2kV/mm field strength
b) electrode-bounded cavity: 10mm x 1mm, tested at 2kV/mm field strength.
Figure 7.15: Statistical response obtained for 14 tests for each of the two types cavity similar to test shown in figures 7.10...7.14. Observe that in both cases a flat cavity has been tested only
a) dielectric-bounded cavity
b) electrode-bounded cavity.

The statistical response derived from 14 tested samples for one type of defect is shown in figure 7.15. Using the following characteristics an electrode-bounded cavity can be recognized, see table 7.5.
To ensure that these results of discharge factor $Q$ and the $mcc$ factor are not due to chance, a significance test was made. It was tested as to whether or not the data set of $Q$ for a dielectric-bounded cavity originates from the same distribution as that of an electrode-bounded cavity. The same was done for the data set of $mcc$. The nonparametric Kolmogorov-Smirnov two-sample test was used. The hypothesis $H_0$: the populations in question originate from the same distribution
7.3. **MULTIPLE CAVITIES**

<table>
<thead>
<tr>
<th>Discriminating Feature</th>
<th>Dielectric-Bounded Flat Cavity</th>
<th>Electrode-Bounded Flat Cavity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Factor $Q$ is small</td>
<td>NO</td>
<td>YES</td>
</tr>
<tr>
<td>Factor $mcc$ is small</td>
<td>NO</td>
<td>YES</td>
</tr>
<tr>
<td>$S_k H_n(\varphi) &gt; S_k H_{eq}(\varphi)$</td>
<td>NO</td>
<td>YES</td>
</tr>
</tbody>
</table>

Table 7.5: Discharges in a flat dielectric- or electrode bounded cavity

(with the two-tailed probability level of 0.9) and were rejected for the data sets of $Q$ and $mcc$.

### 7.3 Multiple cavities

Dielectrics may contain multiple cavities of various sizes. In this case the oscillographic picture has a more complex character and shows intermittent discharges, separately or superimposed. From a technological point of view, it is important to discover this kind of discharge source. Therefore, samples were made with several types of artificial cavities (figure 7.2), as well as sample of $PE$ discs with natural cavities of various sizes. The main objective was to find a characteristic that provides discrimination between dielectric-bounded single and multiple cavities.

All samples were placed in the electrode configuration shown in figure 7.1. An estimation of the inception voltage was made beforehand by using the Paschen curve as an approximation to the breakdown voltage of each cavity. The test voltage was chosen to be 60% above inception voltage.

**DEDUCED QUANTITIES**

The test results obtained in natural multiple cavities in a $PE$ disc will be discussed here. The thickness of the disc was 2mm, there were 11 dielectric-bounded cavities with diameters from 0.5mm up to 4mm. The set-up was subjected to a field strength of 5.7kV/mm.
Figure 7.16: Inception voltage $U_{\text{inc}}(t)$ observed for discharges in multiple cavities: 11 different dielectric-bounded cavities in $PE$, tested at 5.7kV/mm field strength.

Figure 7.17: Maximum discharge magnitude $q_{\text{max}}(t)$ observed for discharges in multiple cavities: 11 different dielectric-bounded cavities in $PE$, tested at 5.7kV/mm field strength.
Figure 7.18: Number of discharges $N_q(t)$ observed for discharges in multiple cavities: 11 different dielectric-bounded cavities in $PE$, tested at 5.7kV/mm field strength.

Figures 7.16, 7.17 and 7.18 show the inception voltage $U_{inc}(t)$, the maximum discharge magnitude $q_{max}(t)$ and the number of discharges $N_q(t)$. All quantities show characteristics similar to those shown by dielectric-bounded single cavities. Less fluctuation in $U_{inc}(t)$ and $N_q(t)$ might possibly be explained by temporary extinctions in part of the cavities caused by the discharge by-products; this tendency is counteracted by the ignition of other cavities caused by local changes in the electric field [8].

STATISTICAL OPERATORS

Figure 7.19: Phase-position quantities $H_{qn}($φ$)$ and $H_n($φ$)$ processed for discharges in multiple cavities: 11 different dielectric-bounded cavities in $PE$, tested at 5.7kV/mm field strength.
The $H_{qn}(\varphi)$ and $H_n(\varphi)$ distributions are shown in figure 7.19. The characteristics which are observed here are given in table 7.6.

<table>
<thead>
<tr>
<th>PHASE-POSITION QUANTITIES</th>
<th>CHARACTERISTICS OF THE DISTRIBUTION</th>
<th>STATISTICAL OPERATORS</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H_{qn}(\varphi)$</td>
<td>asymmetric to the left</td>
<td>Skewness is positive</td>
</tr>
<tr>
<td></td>
<td>flatter than the normal</td>
<td>Kurtosis is negative</td>
</tr>
<tr>
<td></td>
<td>one or two tops</td>
<td>$P e$ is small</td>
</tr>
<tr>
<td></td>
<td>high correlation between the positive half and the negative half of the voltage cycle</td>
<td>$cc$ is high</td>
</tr>
<tr>
<td>$H_n(\varphi)$</td>
<td>asymmetric to the right</td>
<td>Skewness is small and negative</td>
</tr>
<tr>
<td></td>
<td>flatter than the normal distribution</td>
<td>Kurtosis is negative</td>
</tr>
<tr>
<td></td>
<td>one or two tops</td>
<td>$P e$ is small</td>
</tr>
</tbody>
</table>

Table 7.6: Discharges in multiple cavities

Figure 7.20: Statistical operators processed for the $H_{qn}(\varphi)$ and $H_n(\varphi)$ distributions as shown in figure 7.19.

Figure 7.20. shows the values of statistical operators for the distributions $H_{qn}(\varphi)$ and $H_n(\varphi)$ obtained from the sample in $PE$ discussed above.
**Figure 7.21**: Statistical response obtained for 10 tests for multiple cavities similar to test shown in figures 7.16...7.20.

**STATISTICAL RESPONSE**

In figure 7.21, the statistical response is shown for 10 observations made on multiple cavities. Our main objective was to test the discriminating strength with regard to single versus multiple cavities. The comparison between single and multiple cavities provides the following conclusions:

1. For multiple cavities the skewness $Sk$ of $H_n(\varphi)$ is significantly lower than in square or flat cavities.

   If multiple cavities are present, the number of ignited cavities increases as the voltage rises during a half cycle. The result is that most of the cavities ignite just on the advance of the voltage top, resulting in $H_n(\varphi)$ distribution that is asymmetric to the right.

2. For multiple cavities the skewness $Sk$ of $H_{qn}(\varphi)$ is significant higher in contrast to a narrow cavity.

3. For multiple cavities the kurtosis $Ku$ of $H_n(\varphi)$ is negative in contrast to square and flat cavity.

   This is caused by the superimposition of several discharge sources, the $H_n(\varphi)$ distribution of multiple cavities represents a superimposition of several single-cavity distributions, resulting in a flatter distribution.
7.4 Treeing initiated by a point-plane configuration

One of the long-term mechanisms that may cause the breakdown of solids is treeing initiated by conducting inclusions. The treeing phenomenon creates gaseous branches in which partial discharges take place. The mechanism by which an electrical tree starts is only partially understood and will not be discussed here.
When treeing is initiated, discharges of small magnitude occur until minutes before failure. If treeing sets in, breakdown can occur within an extremely short period, in seconds or minutes. Therefore the main subject of this study was (1) to recognize discharges caused by treeing and (2) monitoring the growth of trees.
For this purpose, samples of a point-plane configuration in perspex, with point diameters 40\(\mu\)m, 50\(\mu\)m, 100\(\mu\)m and the distance to the plane 40mm, each was subjected to a test of 20 minutes. To prevent the ignition of unwanted surface discharges the entire configuration was immersed in oil.
To study the growth of trees, optical access to the samples was made possible by using perspex as an insulating material. The optical phenomena were recorded on a video.
The test voltage for these samples was chosen such that the treeing was initiated from the beginning. A test voltage was chosen to reach a field strength of 250kV/mm around the point, using Mason’s formula [90] for point-plane configurations.
The samples, each subjected to a 56-minute test in order to be able to discriminate between the stages: discharges in existing branches only and discharges while growing new branches. To register the changes occurring during the tests, the test time was subdivided into 1 to 2 minutes intervals. For each interval the distributions \(H_{qn}(\varphi)\) were calculated and the skewness \(Sk\) was analyzed off-line.
Figure 7.22: Inception voltage $U_{inc}(t)$ observed for treeing by a point-plane configuration in perspex: point diameter 50$\mu$m, distance to plane 40mm, test voltage of 50kV.

Figure 7.23: Maximum discharge magnitude $q_{\text{max}}(t)$ observed for treeing by a point-plane configuration in perspex: point diameter 50$\mu$m, distance to plane 40mm, test voltage of 50kV.
DEDUCED QUANTITIES
Test results of a point-plane configuration were obtained at 50kV test voltage, using a needle with a point diameter of 50µm. The optical observation and the electrical signals have shown that treeing was initiated from the beginning of the test.

Figure 7.24: Growth of a tree at a point-plane configuration in perspex: point diameter 50µm, distance to plane 40mm, test voltage of 50kV.

In figures 7.22. and 7.23, the time dependence of the inception voltage \( U_{inc}(t) \) and the maximum discharge magnitude \( q_{max}(t) \) are given. It is known that the gaseous by-products can cause an increase in the pressure within the branches so that temporary extinctions of discharges may occur. Leakage along the electrode and diffusion into the dielectric cause re-ignition of discharges. The comparison of both quantities shows that larger discharges occur at higher values of the inception voltage, whereas the decrease of \( U_{inc}(t) \) is attended by a decrease in the maximum discharge magnitude \( q_{max}(t) \). Optical observation has shown that the formation of new trees was intensive when \( q_{max}(t) \) decreased, see figure 7.24. The possible explanation is that large discharges take place in existing large cavities around the point, whereas smaller discharges take place in new small branches, causing the growth of trees.

The number of discharges \( N_q(t) \) represented in figure 7.25 shows a low intensity of discharges during the test.

STATISTICAL OPERATORS
The \( H_qn(\varphi) \) and \( H_n(\varphi) \) distributions, for example, described above are shown in figure 7.26. The characteristics for these distributions
Figure 7.25: Number of discharges $N_q(t)$ observed for treeing by a point-plane configuration in perspex: point diameter 50\,\mu m, distance to plane 40\,mm, test voltage of 50\,kV.

Figure 7.26: Phase-position quantities $H_{q^n}(\varphi)$ and $H_n(\varphi)$ processed for treeing by a point-plane configuration in perspex: point diameter 50\,\mu m, distance to plane 40\,mm, test voltage of 50\,kV.
are given in table 7.7.

**Figure 7.27:** Statistical operators processed for the $H_{q_n}(\varphi)$ and $H_n(\varphi)$ distributions as shown in figure 7.26.

<table>
<thead>
<tr>
<th>PHASE-POSITION QUANTITIES</th>
<th>CHARACTERISTICS OF THE DISTRIBUTION</th>
<th>STATISTICAL OPERATORS</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H_{q_n}(\varphi)$</td>
<td>asymmetric to the right</td>
<td>Skewness is negative</td>
</tr>
<tr>
<td></td>
<td>flatter than the normal</td>
<td>Kurtosis is negative</td>
</tr>
<tr>
<td></td>
<td>one or two tops</td>
<td>$Pe$ is small</td>
</tr>
<tr>
<td></td>
<td>little correlation between the positive half and the negative half of the voltage cycle</td>
<td>$Q$, $cc$ and $mcc$ are small</td>
</tr>
</tbody>
</table>

| $H_n(\varphi)$            | symmetric or less asymmetric to the left | Skewness is zero or small and positive |
|                           | flatter than the normal distribution   | Kurtosis is negative |
|                           | one or two tops                        | $Pe$ is small          |

**Table 7.7:** Treeing initiated by a point-plane configuration

The values of the statistical operators calculated for the above distributions are shown in figure 7.27.
**Figure 7.28:** Single distributions of the phase-position quantities $H_{qn}(\varphi)$ processed during the growth of a tree at a point-plane configuration in perspex: point diameter 50$\mu$m, distance to plane 40mm, test voltage of 50kV.

**Figure 7.29:** Time behaviour of skewness $Sk(t)$ of $H_{qn}(\varphi)$ processed during 56 minutes of the growth of a tree at a point-plane configuration in perspex: point diameter 50$\mu$m, distance to plane 40mm, test voltage of 50kV.
To observe changes of skewness the test time was divided into 1 minute intervals. For each interval the distribution $H_{q_n}(\varphi)$ was processed and off-line analyzed with skewness $Sk$. In figure 7.28, an example of such distributions is given. The example shows that the modus, the median and the shape of the distributions change considerably during the test. To describe these variations for all 56 $H_{q_n}(\varphi)$ distributions, the skewness $Sk(t)$ values were calculated, see figure 7.29. The following characteristics were observed for $Sk(t)$:

- The positive and the negative halves of the voltage cycle show different $Sk(t)$ behaviour.

- The negative half is characterized more than the positive one by negative values of $Sk(t)$, see time intervals 0-8, 14-23, 33-37 and 40-45 minutes.

The comparison of the negative values of $Sk(t)$ with the deduced quantities $q_{\text{max}}(t)$ and $U_{\text{inc}}(t)$ at the negative half of the voltage cycle (figures 7.22, 7.23) provides the following observation:

- In the time intervals 0-8, 14-23, 33-37 and 40-45 minutes the low $U_{\text{inc}}(t)$ is attended by low values of $q_{\text{max}}(t)$.

- Earlier observation has revealed that the formation of new trees is intensive at low values of $q_{\text{max}}(t)$.

The negative values of $Sk(t)$ may be related to the growth of trees. A possible explanation can be given as follows: the distributions $H_{q_n}(\varphi)$ were calculated during 1 minute. During this time all discharges which occurred were stored in one distribution:

- the large discharges in the large cavities are ignited at higher voltage

- the small discharges in the small branches are ignited at lower voltage.

The superimposition of these discharges results in a distribution that is asymmetric to the right, which yields a negative skewness $Sk$ of $H_{q_n}(\varphi)$. 

Figure 7.30: Statistical response obtained for 14 different tests for treeing by a point-plane configuration similar to test shown in figures 7.22...7.29.

**STATISTICAL RESPONSE**

In figure 7.30, the statistical response for 14 different samples is given. The main subject of this study was first, to recognize discharges caused by treeing and, second, the monitoring of the growth of trees. Treeing initiated by a sharp electrode can be recognized by the characteristics given in table 7.8.

<table>
<thead>
<tr>
<th>PHASE-POSITION QUANTITIES</th>
<th>CHARACTERISTIC STATISTICAL OPERATOR</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H_{on}(\varphi)$</td>
<td>Skewness $Sk$ is negative</td>
</tr>
<tr>
<td></td>
<td>Skewness as a function of time $Sk(t)$ is negative during the formation of new trees</td>
</tr>
<tr>
<td></td>
<td>Number of peaks $Pe$ is high</td>
</tr>
<tr>
<td></td>
<td>Factor $mcc$ is low</td>
</tr>
<tr>
<td>$H_{n}(\varphi)$</td>
<td>Kurtosis $Ku$ is negative</td>
</tr>
<tr>
<td></td>
<td>Number of peaks $Pe$ is high</td>
</tr>
</tbody>
</table>

Table 7.8: Recognition of treeing initiated by a point-plane configuration
7.5 Treeing initiated by a cavity

An another long-term mechanism that can cause the breakdown of solids is treeing initiated by a cavity. In this case, partial discharges produce an eroded area at the inner surface. It is followed by the formation of a pit and finally by the generation of an electrical tree. Treeing will start if the electric field at the tip of a formed pit reaches the specific treeing inception value [17]. If this process is initiated, a final dielectric failure is inevitable. The use of the skewness $Sk$ of $H_{q_n}(\varphi)$ was introduced by Tanaka and Okamoto [61] as a check, whether treeing is initiated in a dielectric containing cavity discharges. These authors developed a micro-computer system for on-site diagnostics of XLPE cables. Experiments demonstrated that the skewness of $H_{q_n}(\varphi)$ becomes negative if treeing starts in a cavity. This new parameter was a good tool and yielded extra information in addition to the conventional quantities, like discharge current and discharge magnitude.

The main subject in the present study is first, to recognize treeing caused by cavities and, second, to monitor the change-over from cavity discharges to a cavity with treeing discharges. Therefore tests were made using square and narrow cavities in perspex, see figure 7.2, and using the set-up shown in figure 7.1. To obtain cavities with trees, these samples were aged beforehand.

The test voltage for these samples was chosen such that the field strength in the dielectric was 7 to 10kV/mm.

To monitor the tree initiation, the test time was 20 minutes and was divided into 1 to 2 minutes intervals. For each interval the distribution $H_{q_n}(\varphi)$ was processed and off-line analyzed with skewness $Sk$. Further, the 20 minute tests were repeated several times. Before and after each test an optical check of the cavity was made.

**DEDUCED QUANTITIES**

The results were obtained with a narrow cavity 7mm high, 1mm diameter in perspex, at 50kV test voltage. Before this test, the cavity was stressed three times for 20 minutes per time at the same test voltage; treeing initiation was established in this way. In figures 7.31,
**Figure 7.31:** Inception voltage $U_{inc}(t)$ observed at treeing initiated by a cylindrical cavity in perspex: 1mm x 7mm, tested at 7kV/mm field strength.

**Figure 7.32:** Maximum discharge magnitude $q_{max}(t)$ observed at treeing initiated by a cylindrical cavity in perspex: 1mm x 7mm, tested at 7kV/mm field strength.

**Figure 7.33:** Number of discharges $N_q(t)$ observed at treeing initiated by a cylindrical cavity in perspex: 1mm x 7mm, tested at 7kV/mm field strength.
7.32 and 7.33. the inception voltage $U_{inc}(t)$, the maximum discharge magnitude $q_{max}(t)$ and the number of discharges $N_q(t)$ are given as a function of time. For $U_{inc}(t)$ and $q_{max}(t)$ is characteristic that after 1 minute of the testing decrease occurs. At the same time an increase is observed in $N_q(t)$. Probably, in this time interval the tree initiation has taken place, which is represented by the above-mentioned changes. After these changes, the discharges in the cavity superimposed with the discharges in trees show relative constant behaviour, observed in all quantities. Only at the end of the test were some increases in $q_{max}(t)$ and $U_{inc}(t)$ observed which were accompanied by a decrease in the number of discharges $N_q(t)$. These changes can be well connected to the extinction of discharges in the tree branches caused by discharge by-products. It could result into the comeback of discharging conditions before treeing has ignited.

![Diagram](image)

**Figure 7.34:** Phase-position quantities $H_{qn}(\phi)$ and $H_n(\phi)$ processed at treeing initiated by a cylindrical cavity in perspex: 1mm x 7mm, tested at 7kV/mm field strength.

**STATISTICAL OPERATORS**

The $H_{qn}(\phi)$ and $H_n(\phi)$ distributions for example described above are shown in figure 7.34. The characteristics for these distributions are given in table 7.9.

The values of the statistical operators calculated for the example discussed above are shown in figure 7.35. In figure 7.36, the results of an optical check made before and after the 20 minutes test, are shown.
<table>
<thead>
<tr>
<th>PHASE-POSITION QUANTITIES</th>
<th>CHARACTERISTICS OF THE DISTRIBUTION</th>
<th>STATISTICAL OPERATORS</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H_{q_n}(\varphi)$</td>
<td>symmetric or asymmetric to the right</td>
<td>Skewness is zero or negative</td>
</tr>
<tr>
<td></td>
<td>flatter than the normal</td>
<td>Kurtosis is negative</td>
</tr>
<tr>
<td>two or three tops</td>
<td></td>
<td>$Pe$ is small</td>
</tr>
<tr>
<td>high correlation between the positive half and the negative half of the voltage cycle</td>
<td>$cc$ is high and $Q$, $mcc$ are small</td>
<td></td>
</tr>
<tr>
<td>$H_n(\varphi)$</td>
<td>less asymmetric to the left</td>
<td>Skewness is small and positive</td>
</tr>
<tr>
<td></td>
<td>flatter than the normal distribution</td>
<td>Kurtosis is negative</td>
</tr>
<tr>
<td>two or three tops</td>
<td></td>
<td>$Pe$ is small</td>
</tr>
</tbody>
</table>

Table 7.9: Treeing initiated by a cavity

Figure 7.35: Statistical operators processed for the $H_{q_n}(\varphi)$ and $H_n(\varphi)$ distributions as shown in figure 7.34.
CHAPTER 7. DISCHARGES IN SOLID MATERIALS

Figure 7.36: Photographs of the cavity tested in 7.31...7.35.
   a) before the test
   b) after the test

Figure 7.37: Single distributions of the phase-position quantities $H_{qn}(\varphi)$ processed during treeing initiated by a cylindrical cavity in perspex: 1mm x 7mm, tested at 7kV/mm field strength.
Figure 7.38: Time behaviour of skewness $Sk(t)$ of $H_{qn}(\varphi)$ processed during 20 minutes treeing initiated by a cylindrical cavity in perspex: 1mm x 7mm, tested at 7kV/mm field strength
a) during the test, before the treeing has been initiated
b) during the test when the treeing has been initiated.
CHAPTER 7. DISCHARGES IN SOLID MATERIALS

SKEWNESS AS A FUNCTION OF TIME
To monitor tree initiation, 10 distributions of $\text{H}_{qn}(\varphi)$ were calculated (every 1 minute one distribution) during the test and analyzed off-line with skewness $Sk$. These distributions are shown in figure 7.37. In figure 7.38, two observations of skewness functions $Sk(t)$ are shown as a function of time:

(A) - observed before the treeing was initiated,
(B) - observed with treeing present.

The following characteristics were observed for $Sk(t)$:

- In the (A) and in the (B) case the positive and the negative halves of the voltage cycle showed different $Sk(t)$ behaviour.
- In contrast to cavity discharges (A), treeing discharges (B) were characterized by negative values of the $Sk(t)$ at the positive and the negative halves of the voltage cycle.
- For treeing discharges (B), the negative half had lower values than the positive one.

The comparison in the (B) case of $Sk(t)$ with the deduced quantities $U_{inc}(t)$ and $q_{max}(t)$ for the negative half of the voltage cycle (figures 7.31, 7.32) shows that in the time interval 2-17 minutes, the low $U_{inc}(t)$ is attended by low values of $q_{max}(t)$. Also in this time interval the skewness is negative. This relationship has been also found by the treeing initiated by a sharp electrode (see section 7.4). Earlier in this chapter the observation was made that the formation of new trees was intensive at low values of $q_{max}(t)$: the negative values of $Sk(t)$ may be related to the growth of trees.

In a way similarly to the treeing on a sharp electrode, the asymmetry of the $\text{H}_{qn}(\varphi)$ distributions also results from the superimposition of two discharge sources: cavity discharges and discharges in tree branches. This $Sk$ behaviour in relation to treeing initiated by a cavity confirms the results presented by Tanaka and Okamoto [61].
Figure 7.39: Statistical response obtained for 8 tests for treeing discharges initiated by a cylindrical cavity similar to test shown in figures 7.31...7.34.

**STATISTICAL RESPONSE**

In figure 7.39, the statistical response for 8 different observations is given. Using the characteristics shown in table 7.10, the treeing initiated by a cavity can be recognized.

<table>
<thead>
<tr>
<th>PHASE-POSITION QUANTITIES</th>
<th>CHARACTERISTIC STATISTICAL OPERATOR</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H_qn(\varphi)$</td>
<td>Skewness $Sk$ is small</td>
</tr>
<tr>
<td></td>
<td>Skewness as a function of time $Sk(t)$ becomes negative during the tree initiation and tree growth</td>
</tr>
<tr>
<td></td>
<td>Number of peaks $Pe$ is small</td>
</tr>
<tr>
<td>$H_n(\varphi)$</td>
<td>Kurtosis $Ku$ is negative</td>
</tr>
<tr>
<td></td>
<td>Number of peaks $Pe$ is small</td>
</tr>
</tbody>
</table>

Table 7.10: Recognition of treeing initiated by a cavity
CHAPTER 7. DISCHARGES IN SOLID MATERIALS

7.6 Conclusions on partial discharges in solid materials

Tests on various defects in solid materials have led to the following conclusions:

1. Conclusions related to the time dependency of deduced quantities:
   - In cavities the inception voltage $U_{inc}(t)$ increases after 5 to 10 minutes of voltage application.
   - In cavities the number of discharges $N_q(t)$ decreases sometimes. This decrease is sometimes attended by a decrease in the maximum discharge magnitude $q_{max}(t)$.
   - When there are treeing discharges than an increase in the number of discharges $N_q(t)$ can occur, due to formation of new hollow spaces containing partial discharges.
   - Electrode-bounded cavities are characterized by the difference in the inception voltage $U_{inc}(t)$ in the positive and the negative half of the voltage cycle.

2. Conclusions related to statistical response:
   Table 7.11 shows the discriminating features for discharges in solid materials obtained by means of the statistical responses of these defects.
<table>
<thead>
<tr>
<th>DISCRIMINATING FEATURE</th>
<th>SINGLE CAVITY</th>
<th>MULTIPLE CAVITIES</th>
<th>TREEING ON A CONDUCTOR</th>
<th>TREEING ON A CAVITY</th>
</tr>
</thead>
<tbody>
<tr>
<td>Skewness $Sk$ on $H_{qn}(\phi)$ is negative</td>
<td>square: NO</td>
<td>NO</td>
<td>YES</td>
<td>YES</td>
</tr>
<tr>
<td></td>
<td>flat: NO</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>narrow: YES</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Skewness $Sk$ on $H_n(\phi)$ is high and positive</td>
<td>square: YES</td>
<td>NO</td>
<td>NO</td>
<td>NO</td>
</tr>
<tr>
<td></td>
<td>flat: YES</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>narrow: NO</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Kurtosis $K'u$ on $H_n(\phi)$ is negative</td>
<td>square: NO</td>
<td>YES</td>
<td>YES</td>
<td>YES</td>
</tr>
<tr>
<td></td>
<td>flat: NO</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>narrow: YES</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Factor $mcc$ is small</td>
<td>dielectric-bounded: NO</td>
<td>NO</td>
<td>YES</td>
<td>YES</td>
</tr>
<tr>
<td></td>
<td>electrode-bounded: YES</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Number of peaks $Pe$ on $H_{qn}(\phi)$ and $H_n(\phi)$ is small</td>
<td>YES</td>
<td>YES</td>
<td>NO</td>
<td>YES</td>
</tr>
</tbody>
</table>

Table 7.11: Discharges in solid materials
Chapter 8
Discharge pattern recognition

The preceding study of 14 different discharge sources has illustrated that both the behaviour of the deduced quantities and statistical operators may be used to characterize a defect. To discriminate between discharge pulses of these defects and unwanted signals, a study has been made of the statistical response of noise signals.

8.1 System noise

In spite of the fact that noise from a detection circuit is suppressed as much as possible, circuit noise might reach the analyzer as an unwanted signal. In order to discriminate between system noise and discharge pulses, a noise suppression factor $D_n$ was introduced, see chapters 3 and 4. To obtain a statistical response of noise signals the following values for the noise suppression factor were studied:

$$D_n = 1\%, \ 2\%, \ 3\%, \ 5\%, \ 7\%, \ 9\%,$$

In this example, the maximum discharge measured $S_{max}$ was equivalent to 10pC and the noise band was equivalent to 0.7pC a’ 0.8pC. In figure 8.1, the schematic diagram of noise suppression is shown.

The level of $D_n$ represents the threshold value: only signals above this value are analyzed. This diagram illustrates clearly that for this specific discharge detector the value of $D_n = 10\%$ provides a total suppression of system noise.
The phase-position quantities $H_{qn}(\varphi)$ and $H_n(\varphi)$ are shown in figure 8.2. Both quantities show differences between $D_n$ up to 3% and $D_n = 7\%$ or $D_n = 9\%$.

The following characteristic features for $H_{qn}(\varphi)$ and $H_n(\varphi)$ distributions are observed, see table 8.1.

<table>
<thead>
<tr>
<th>PHASE-POSITION QUANTITIES</th>
<th>CHARACTERISTICS OF THE DISTRIBUTION</th>
<th>STATISTICAL OPERATORS</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H_{qn}(\varphi)$</td>
<td>symmetric or less asymmetric to the right</td>
<td>Skewness is zero or small negative</td>
</tr>
<tr>
<td></td>
<td>flatter than the normal distribution</td>
<td>Kurtosis is negative</td>
</tr>
<tr>
<td></td>
<td>several tops</td>
<td>$P_e$ is high</td>
</tr>
<tr>
<td></td>
<td>almost the same magnitude of the distributions in the positive half and the negative half of the voltage cycle</td>
<td>$Q$ is high</td>
</tr>
<tr>
<td>$H_n(\varphi)$</td>
<td>symmetric or less asymmetric to the right</td>
<td>Skewness is zero or small and negative</td>
</tr>
<tr>
<td></td>
<td>flatter than the normal distribution</td>
<td>Kurtosis is negative</td>
</tr>
<tr>
<td></td>
<td>several tops</td>
<td>$P_e$ is high</td>
</tr>
</tbody>
</table>

**Table 8.1:** System noise

The values of the statistical operators of the phase-position quantities calculated for these four examples of noises are shown in figure 8.3.
Figure 8.2: Phase-position quantities $H_{\text{sn}}(\varphi)$ and $II_{\text{n}}(\varphi)$ processed for system noise using different values of noise suppression factor $D_n$.

- $D_n = 1\%$
- $D_n = 3\%$
- $D_n = 7\%$
- $D_n = 9\%$
Figure 8.3: Statistical operators processed for $H_q(n, \varphi)$ and $H_n(\varphi)$ distributions shown in figure 8.2.

a) $D_n = 1\%$  b) $D_n = 3\%$  c) $D_n = 7\%$  d) $D_n = 9\%$

Figure 8.4: Statistical response of 8 tests made for system noise.
8.2. **STATISTICAL RECOGNITION**

In figure 8.4, the statistical response of 8 tests made for system noise is shown. The comparison of statistical operators: skewness $Sk$, kurtosis $Ku$ and the number of peaks $Pe$ calculated for $H_{qn}(\varphi)$ and $H_{n}(\varphi)$, shows that there are no significant differences between the positive half and of the negative half of the voltage cycle. That the system noise might possibly be recognized from other discharges sources is demonstrated later by the comparison between the statistical response of system noise and that of actual discharge sources, see figure 8.14.

### 8.2 Statistical recognition

In order to recognize discharge sources, a systematic approach has to be found, using the statistical responses introduced in the former chapters. *The behaviour of deduced quantities as a function of time were not further used in this thesis.*

An algorithm is sought after to recognize an unknown discharge source from its statistical operators. Therefore, a simple algorithm will be tested here; if positive results are obtained, then these data may provide in the future the basis for more advanced methods of recognition.

**COMPARISON OF STATISTICAL RESPONSES**

In the preceding tests, 15 discharge sources were analyzed, each characterized by 15 statistical operators. Several observations were made for each defect, resulting in 15 data-sets per defect. In total, 225 data-sets were determined, covering all the defects. For each set, the mean values $M_{so}$ (with 95% confidence intervals) were processed, giving the statistical response for a defect.

Before these statistical responses were compared, a test was made to see whether all these 225 data-sets are normally distributed. Using the nonparametric Kolmogorov-Smirnov one-sample test, the 225 data-sets, were compared to a hypothesized normal distribution. For all 225 data-sets the hypothesis $H_0$ (the population in question is normally distributed) was accepted with a two-tailed probability level of 0.95.
Figure 8.5: Comparison of values of one and the same statistical operator as obtained for the different 15 defects.
a) skewness $Sk$ of $H_{qn}(\varphi)$
b) skewness $Sk$ of $H_n(\varphi)$
c) kurtosis $Ku$ of $H_{qn}(\varphi)$
d) kurtosis $Ku$ of $H_n(\varphi)$

Figure 8.6: Comparison of values of one and the same statistical operator as obtained for the different 15 defects.
a) number of local peaks $Pe$ of $H_{qn}(\varphi)$
b) number of local peaks $Pe$ of $H_n(\varphi)$
Figure 8.7: Comparison of values of one and the same statistical operator as obtained for the different 15 defects.

a) discharge factor $Q$

b) cross-correlation factor $cc$

c) modified cross-correlation factor $mcc$
To discriminate between defects, a survey is given of all operators in use. The figures 8.5, 8.6 and 8.7 show the values of one and the same statistical operator for all 15 defects.

Looking at one statistical operator: one or several defects can be characterized with this operator, see for instance, in figure 8.6 the number of peaks $P_e$ of $H_{qn}(\varphi)$. Sometimes these differences occur at one statistical operator only, and cannot be found again by another operator, compare, for instance, the number of peaks $P_e$ of $H_{qn}(\varphi)$ in figure 8.6 to the skewness $Sk$ of $H_{qn}(\varphi)$ in figure 8.5. The conclusion is that combining the statistical operators may give more discrimination strength than the comparison of single values of statistical operators.

**RECOGNITION RATE**

In foregoing chapters 5, 6, and 7 the analysis of different discharge sources has defined for each defect the statistical response. This statistical response is based on a data-set obtained from several observations of each defect. The $C_{2.5\%}$ and $C_{97.5\%}$ quartiles of each statistical operator of a defect were processed, representing the 95% confidence intervals covering the mean value $M_{x0}$ of the estimated true population, see chapter 4 the equation (4.1). These quartiles are called limits of the statistical response.

For an arbitrary discharge measurement characterized by its statistical operators $X_{op}$, the notion recognition rate was introduced. The recognition rate represents the number of statistical operators that fit in the limits given by the statistical responses of the 15 known discharge sources. In figure 8.8, an arbitrary example of an unknown discharge source is shown.

Using a matrix, the statistical operators $X_{op}$ of an unknown defect are compared to the statistical response of the 15 known discharge sources, see figure 8.8a. The number of statistical operators (minimum 0, maximum 15) fitting in the interval of the statistical response of a defect is determined; the highest recognition rate indicates the type of defect. In this particular case, the highest recognition rate indicates that there are surface discharges in air, see figure 8.8b.

Figures 8.9 to 8.14 show the recognition rates of the 15 artificial defects that were studied throughout this thesis: (for each defect the
### 8.2. Statistical Recognition

<table>
<thead>
<tr>
<th>Source</th>
<th>Sk Hn(d1)</th>
<th>Sk Hn(d2)</th>
<th>Pa Hn(d1)</th>
<th>Pa Hn(d2)</th>
<th>Q</th>
<th>CC</th>
<th>MCC</th>
<th>Recognition Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Square Cavity</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>X</td>
<td>-</td>
<td>7</td>
</tr>
<tr>
<td>Flat Cavity</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>X</td>
<td>-</td>
<td>5</td>
</tr>
<tr>
<td>Narrow Cavity</td>
<td>X</td>
<td>X</td>
<td>-</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>-</td>
<td>9</td>
</tr>
<tr>
<td>Multiple Cavities</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>X</td>
<td>-</td>
<td>5</td>
</tr>
<tr>
<td>Dielectric Bounded Cavity</td>
<td>-</td>
<td>-</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>-</td>
<td>9</td>
</tr>
<tr>
<td>Electrode Bounded Cavity</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>-</td>
<td>8</td>
</tr>
<tr>
<td>Treating on an Electrode</td>
<td>X</td>
<td>X</td>
<td>-</td>
<td>X</td>
<td>-</td>
<td>X</td>
<td>-</td>
<td>6</td>
</tr>
<tr>
<td>Treating on a Cavity</td>
<td>X</td>
<td>X</td>
<td>-</td>
<td>X</td>
<td>-</td>
<td>X</td>
<td>-</td>
<td>7</td>
</tr>
<tr>
<td>Surface Discharges in Air</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>-</td>
<td>14</td>
</tr>
<tr>
<td>Surface Discharges in SF6</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>X</td>
<td>-</td>
<td>9</td>
</tr>
<tr>
<td>Surface Discharges in Oil</td>
<td>X</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>X</td>
<td>-</td>
<td>5</td>
</tr>
<tr>
<td>Corona Discharges in Air</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>X</td>
<td>-</td>
<td>3</td>
</tr>
<tr>
<td>Corona Discharges in Oil</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>X</td>
<td>-</td>
<td>3</td>
</tr>
<tr>
<td>Floating Parts</td>
<td>X</td>
<td>X</td>
<td>-</td>
<td>X</td>
<td>-</td>
<td>X</td>
<td>-</td>
<td>5</td>
</tr>
<tr>
<td>System Noise</td>
<td>X</td>
<td>X</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>X</td>
<td>-</td>
<td>2</td>
</tr>
</tbody>
</table>

- **X:** statistical operator fits in the statistical response of a defect
- **-:** statistical operator does not fit in the statistical response of a defect

(a)

![Figure 8.8](image.png)

**Figure 8.8:** Example of recognition of an unknown defect with the aid of the statistical operators.

a) matrix for comparison of an unknown discharge source with the statistical responses of 15 known discharge sources

b) graphic output of the recognition rate processed in (a)
Figure 8.9: Recognition rates of discharges in gases. The defect in question is representing the mean value $M_{so}$ of many tests was entered.

a) corona discharges in air
b) floating parts
c) surface discharges in air
d) surface discharges in $SF_6$
8.2. **STATISTICAL RECOGNITION**

![Graphs showing discharge rates in oil](image)

**Figure 8.10:** Recognition rates of discharges in liquids. The defect in question is representing the mean value $M_{so}$ of many tests was entered.

a) corona discharges in oil
b) surface discharges in oil

mean values of statistical operator $M_{so}$ were entered). It is evident that for the defect itself all 15 operators match the confidence intervals, resulting in a total recognition (see the light bars).

These diagrams illustrate clearly that each defect is characterized by a significant combination of 15 statistical operators. There are no cases in which more than one defect has the maximal recognition of 15 operators. But in several cases the recognition rates of two defects show a certain similarity, see, for instance, the "floating parts" and "treeing on a cavity" in figure 8.9b, or the "treeing on a cavity" and the "multiple cavities" in figure 8.13.

Therefore a value $\Delta_{op}$ is introduced, representing the smallest difference with the next best recognition rate, see $\Delta_{op}$ in the figure 8.9. In table 8.2 comparison of the value $\Delta_{op}$ for all 15 defects is shown. The low value of $\Delta_{op}$ of some defects may be due to the fact that not all defects are independent, for instance, the dielectric-bounded cavity studied here happened to be a flat cavity, see section 7.2. This could result in a higher recognition rate for a dielectric-bounded cavity and
Figure 8.11: Recognition rates of discharges in solid materials where for the defect the mean value $M_{so}$ of many tests was entered.

a) dielectric-bounded square cavity
b) dielectric-bounded flat cavity
c) dielectric-bounded narrow cavity
### 8.2. STATISTICAL RECOGNITION

<table>
<thead>
<tr>
<th>DISCHARGE SOURCE</th>
<th>RECOGNITION DISTANCE $\Delta_{op}$</th>
<th>ALTERNATIVE DISCHARGE SOURCE(S) WITH A RECOGNITION DISTANCE $\Delta_{op}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>SQUARE CAVITY dielectric-bounded</td>
<td>•••</td>
<td>DIELECTRIC-BOUNDDED CAVITY SURFACE DISCHARGES IN $SF_6$ FLAT CAVITY</td>
</tr>
<tr>
<td>FLAT CAVITY dielectric-bounded</td>
<td>•</td>
<td>DIELECTRIC-BOUNDDED CAVITY</td>
</tr>
<tr>
<td>NARROW CAVITY dielectric-bounded</td>
<td>••••••</td>
<td>SQUARE CAVITY DIELECTRIC-BOUNDDED CAVITY ELECTRODE-BOUNDDED CAVITY TREEING ON A CAVITY SURFACE DISCHARGES IN $SF_6$</td>
</tr>
<tr>
<td>MULTIPLE CAVITIES dielectric-bounded</td>
<td>••••••</td>
<td>TREEING ON A CAVITY</td>
</tr>
<tr>
<td>DIELECTRIC-BOUNDDED CAVITY square and flat</td>
<td>••••••</td>
<td>FLAT CAVITY ELECTRODE-BOUNDDED CAVITY</td>
</tr>
<tr>
<td>ELECTRODE-BOUNDDED CAVITY square and flat</td>
<td>••••••</td>
<td>SQUARE CAVITY FLAT CAVITY NARROW CAVITY SURFACE DISCHARGES IN $SF_6$</td>
</tr>
<tr>
<td>TREEING INITIATED ON AN ELECTRODE</td>
<td>••••••</td>
<td>TREEING ON A CAVITY</td>
</tr>
<tr>
<td>TREEING INITIATED ON A CAVITY</td>
<td>•••</td>
<td>TREEING ON AN ELECTRODE</td>
</tr>
<tr>
<td>SURFACE DISCHARGES IN AIR</td>
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<td>NARROW CAVITY</td>
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<td>SURFACE DISCHARGES IN $SF_6$</td>
<td>••••••</td>
<td>SQUARE CAVITY</td>
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<tr>
<td>SURFACE DISCHARGES IN OIL</td>
<td>••••••</td>
<td>NARROW CAVITY TREEING ON AN ELECTRODE</td>
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<tr>
<td>CORONA DISCHARGES IN AIR</td>
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<td>NARROW CAVITY</td>
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<tr>
<td>CORONA DISCHARGES IN OIL</td>
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<td>TREEING ON AN ELECTRODE</td>
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<td>FLOATING PARTS</td>
<td>•••</td>
<td>TREEING ON A CAVITY</td>
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<tr>
<td>SYSTEM NOISE</td>
<td>••••••</td>
<td>TREEING ON AN ELECTRODE</td>
</tr>
</tbody>
</table>

- number of operators not fitting in the statistical response of another defect

**Table 8.2:** Nearest recognition rates of all defects
Figure 8.12: Recognition rates of discharges in solid materials. The defect in question is representing the mean value $M_{so}$ of many tests was entered.

a) dielectric-bounded cavity  
b) electrode-bounded cavity

A higher recognition rate for a flat cavity. There is thus ample room for extending this table by further research. Another explanation could well be the similarities of the discharge processes of some defects, for instance, treeing on an electrode, treeing on a cavity, multiple cavities or a narrow cavity.
8.2. STATISTICAL RECOGNITION

Figure 8.13: Recognition rates of discharges in solid materials. The defect in question is representing the mean value $M_{so}$ of many tests was entered.

- a) dielectric-bounded multiple cavities
- b) treeing initiated by a sharp electrode
- c) treeing initiated by a cavity

Figure 8.14: Recognition rates of system noise. The defect in question is representing the mean value $M_{so}$ of many tests was entered.
8.3 Conclusions on the discharge pattern recognition

To summarize, the following conclusions can be drawn:

1. System noise can be well separated from real discharges sources when using the noise suppression factor of $D_n = 10\%$.

2. All 225 data-sets of statistical operators processed for the 15 discharge sources were normally distributed (with a two-tailed probability level of 0.95).

3. Each of the 15 artificial defects is characterized by a typical combination of the statistical operators obtained at the discharge test.
Chapter 9
Analysis of technical objects

The objective of this chapter is to apply the recognition rate to the diagnosis of technical objects. Therefore discharges were analyzed in the following five objects:

- Bushing: 10kV/ 300A
- Current transformer 2x150A to 5A for 50kV systems
- PE cable 6/10kV
- 3-core belted PVC cable 10kV
- Bushing 150kV.

The objects were subjected to a constant a.c. voltage. The test voltage was chosen to be at a level where no extinction of discharges was expected. The value of the test voltage will be presented with the measuring results.

No rules were used to determine the test time, the test period varied between 3 minutes and 20 minutes.

The results of the measurements were analyzed using the 15 statistical operators. Based on the highest recognition rate, the indication of a possible type of defect will be discussed. Further, the indication of the second highest recognition rate will be taken into account. To confirm these statements, in some of the cases, the origins of the discharges were discovered using an ultrasonic detection system (surface discharges), or the confirmation was based on the knowledge of the occurrence of a defect.
9.1 Bushing 10kV/300 A

Typically, for medium voltage distribution, the bushing 10kV/300A, provides a measurement of the primary current. This apparatus is composed of an epoxy resin insulator, current-measuring windings and an earthed casing.

![Diagram of bushing](image)

**Figure 9.1:** Cross-section of the 10kV/300A bushing with indications of possible discharge sites.

The cross-section of the bushing is shown in figure 9.1. In this figure the critical sites where discharges can occur are shown. First, the metal casing that makes contact with the epoxy resin insulator may cause surface discharges, see discharge sites (A). Second, the conducting layer on the insulator can adhere badly to the epoxy resin resulting in an electrode-bounded cavity, see discharge sites (B). Further, the insulating varnish covering the conducting layer may only partly fill the above-mentioned cavity resulting in a dielectric-bounded cavity, see discharge sites (B). To analyze both discharge sites the apparatus was subjected to test of 20 minutes using a straight detection circuit.

First, the complete object was subjected to a 17kV test voltage. In figure 9.2, the phase-position quantities the $H_{qn}(\varphi)$ and $H_n(\varphi)$ are
9.1. BUSHING 10KV/300 A

![Graph](image)

**Figure 9.2:** Phase-position quantities $H_{qn}(\varphi)$ and $H_n(\varphi)$ processed during a 20 minutes test on a complete 10kV/300A bushing at a test voltage of 17kV.

These distributions were analyzed using statistical operators, see figure 9.3.

![Graph](image)

**Figure 9.3:** Statistical operators for the phase-position quantities $H_{qn}(\varphi)$ and $H_n(\varphi)$ shown in figure 9.2.

The *recognition rate* in figure 9.4. shows that the highest value occurs at "surface discharges in air". This result may be correlated to the discharge sites (A).

Ultrasonic detection has confirmed the cause of these discharges. The second high *recognition rate* of "flat cavity" indicates cavity discharges that may be correlated to the discharge sites (B).

Second, the casing was removed and the bushing was subjected to an 18kV test voltage. In figure 9.5 the distributions $H_{qn}(\varphi)$ and $H_n(\varphi)$ are shown.
**Figure 9.4:** Recognition rate obtained for the test on the complete 10kV/300A bushing at the test voltage of 17kV.

**Figure 9.5:** Phase-position quantities $H_{qn} (\varphi)$ and $H_n (\varphi)$ processed during a 20 minutes test on the 10kV/300A bushing (without the casing) at a test voltage of 18kV.
The statistical operators processed for these distributions as well as the recognition rate are shown in figures 9.6 and 9.7.

![Figure 9.6: Statistical operators for the phase-position quantities $H_{qn}(\varphi)$ and $H_{n}(\varphi)$ shown in figure 9.5.](image)

![Figure 9.7: Recognition rate obtained for the test on the 10kV/300A bushing (without the casing) at a test voltage of 18kV.](image)

In this case when the casing was removed significant difference occurs compared to the first test, where surface discharges in air were found. The highest value of the recognition rate shows an "electrode-bounded cavity". Here the origin of the discharges reveals a cavity or cavities between the conducting layer, the epoxy resin insulator and the insulating varnish. The second highest recognition rate for "dielectric-bounded cavity" may be correlated to a cavity or cavities where the insulating lake covers the conducting layer, resulting in a dielectric-bounded cavity.
An interesting result is that corrections in the construction of both critical parts of the bushing have led to the disappearance of discharges. In figures 9.8 and 9.9, the photographs of bushing with indications of defects, are shown.

Figure 9.8: Photograph of the complete 10kV/300A bushing.

Figure 9.9: Photograph of the 10kV/300A bushing without casing.
9.2 Current transformer 2x150A to 5A

The current transformer 2 x 150A to 5A is used in 50kV transmission networks. These transformers are tested for 1 second at 30kA short circuit current. Because of mechanical stresses during this test the epoxy resin sometimes cracks. This results in cavities around the transformer core igniting at a voltage lower than the phase voltage, 29kV r.m.s.

Discharge measurement was carried out after such a short-circuiting test. The cross-section of the current transformer and the indication of possible defects is shown in figure 9.10.

![Figure 9.10: Cross-section of the 2x150A to 5A current transformer with indications of possible discharge sites.](image)

Using a straight detection circuit, the transformer was subjected to a 35kV test voltage throughout the 3 minutes. In figure 9.11, the phase-position quantities the \( H_\text{avg}(\varphi) \) and \( H_n(\varphi) \) are shown. The statistical operators processed for these distributions are shown in figure 9.12.

The recognition rate for these statistical operators indicates that there is a "dielectric-bounded cavity", see figure 9.13. Also a "narrow cavity" is indicated which has higher values than that of other defects.
CHAPTER 9. ANALYSIS OF TECHNICAL OBJECTS

Figure 9.11: Phase-position quantities $H_{q}(\varphi)$ and $H_{n}(\varphi)$ processed during a 3 minutes test on the 2x150A to 5A current transformer at a test voltage of 35kV.

Figure 9.12: Statistical operators for the phase-position quantities $H_{q}(\varphi)$ and $H_{n}(\varphi)$ shown in figure 9.11.

Figure 9.13: Recognition rate obtained for the test on the 2x150A to 5A current transformer tested at 35kV.
In figure 9.14, a photograph of this current transformer is shown. Both the defects recognized are realistic and could occur around the core after mechanical stress during the short circuit test.

![Photograph of the 2x150A to 5A current transformer.](image)

An affirmation of this recognition could not be given. Further destroying of the transformer would not be the right way to confirm this indication because the destruction would damage the defects themselves.

### 9.3 6/10kV PE cable

To analyze the discharges in a high-voltage cable, two typical defects were studied: treeing at a sharp electrode and discharges in an electrode-bounded cavity. These defects were made artificially. They were placed in the middle of a 1m long 6/10kV cable, see figure 9.15. To obtain a good screening of the measuring electrode, the electrode was covered with insulating paper and an earthed copper screen.

First, to obtain treeing discharges, a stainless steel needle with a radius of 50µm was inserted to 1,15mm depth into the insulation. The PE cable with the needle was aged 100 minutes at 28kV test voltage. Treeing was initiated from the beginning of the test. Then the cable was subjected to a 5 minutes test at 42kV test voltage.
CHAPTER 9. ANALYSIS OF TECHNICAL OBJECTS

Figure 9.15: Cross-section of the 6/10kV PE cable with the site of artificial defects.

During this time, the phase-position quantities $H_{qn}(\varphi)$ and $H_{n}(\varphi)$ were processed, see figure 9.16.

Figure 9.16: Phase-position quantities $H_{qn}(\varphi)$ and $H_{n}(\varphi)$ processed during a 5 minutes test on the 6/10kV PE cable with treeing discharges at a test voltage of 42kV.

The statistical operators processed for these distributions are shown in figure 9.17. In figure 9.18, the recognition rate clearly indicates "treeing at an electrode".

The second highest value of the recognition rate indicates a "narrow cavity". The explanation may be that discharges in the hollow trunk
9.3. 6/10KV PE CABLE

Figure 9.17: Statistical operators for the phase-position quantities $H_q(\varphi)$ and $H_n(\varphi)$ shown in figure 9.16.

Figure 9.18: Recognition rate obtained for the test on the 6/10kV PE cable with treeing discharges at a test voltage of 42kV.
of the tree have characteristics similar to a narrow cavity. A photograph of this PE cable is shown in figure 9.19a. A confirmation of the explanation discussed above is given in figure 9.19b, where the breakdown channel of the cable is shown.

Figure 9.19: Photograph of 6/10kV PE cable.

a) cable sample
b) breakdown channel after the test

Second, to obtain discharges in an electrode-bounded cavity, a cylin-
rical cavity with a 1mm diameter and 1mm height was made within the PE insulation, see figure 9.15. Using a straight detection circuit, the cable was subjected to a 42kV test voltage throughout the 20 minutes. In figure 9.20, the phase-position quantities $H_{qn}(\varphi)$ and $H_n(\varphi)$ are shown.

![Graph showing phase-position quantities](image)

**Figure 9.20:** Phase-position quantities $H_{qn}(\varphi)$ and $H_n(\varphi)$ processed during a 20 minutes test at the 6/10kV PE cable with an electrode-bounded cavity at a test voltage of 42kV.

The statistical operators processed for these distributions are shown in figure 9.21. The *recognition rate* indicates an "electrode-bounded cavity", see figure 9.22.

![Cavity discharges on a 10 kV PE cable](image)

**Figure 9.21:** Statistical operators for the phase-position quantities $H_{qn}(\varphi)$ and $H_n(\varphi)$ shown in figure 9.20.

The shape of the cavity could not be recognized because the same value for the *recognition rate* is given for different shapes of cavities.
This happens because the recognition rate in preceding chapters was developed to discriminate between dielectric-bounded and electrode-bounded cavities only; different shapes of an electrode-bounded cavity have not yet been studied.

## 9.4 3-core belted PVC 10kV cable

To analyze the discharges in a three-phase configuration, a three-core belted-type cable rated for 10kV was tested. Because the electric field in a three-phase construction rotates, and the shape of the field changes continuously, discharge detection is more difficult than in single phase constructions.

In practice, using possible detection circuits that can be chosen for three-phase constructions discharges can well be located in one of the six possible combinations of the core and the belt insulation [91]. It is known that the partial discharges in this type of cable occur in air gaps between the cores in the centre of the cable or at the 'corners' between a core and the belt insulation, see figure 9.23.

The investigations were carried out on an aged 6.5 meters long cable with discharge free terminations under oil. The cable was energized at three-phase voltage. In figure 9.23 the schematic cross-section of this cable as well as the measuring set-up are shown.

Using a straight detection circuit, measurements were carried out for each of the conductors $R$, $S$ and $T$. For this purpose the cable
sheath was earthed and the three phases were connected through coupling capacitors to the detection resistor. For all three tests the phase-position $H_q(\varphi)$ and $H_n(\varphi)$ were related to the voltage of the conductor $R$. For all three tests the cable was subjected throughout the 5 minutes to 5kV test voltage.

In figures 9.24, the quantities the $H_q(\varphi)$ and $H_n(\varphi)$ obtained at the conductor $S$ are shown. The statistical operators processed for these distributions are shown in figure 9.25. The recognition rate does not give a clear indication of a defect, see figure 9.26.

In figure 9.27, the phase-position quantities $H_q(\varphi)$ and $H_n(\varphi)$ for the measurement at the conductor $T$ are shown. These distributions were also analyzed using statistical operators, see figure 9.28. The recognition rate in figure 9.29 does not indicate a particular defect, similar to the test on conductor $S$.

It is not surprising that the analysis does not recognize these discharges, because discharges in such a three-core configuration are not included in the data of the 15 physical models with known defects.

In figure 9.30, phase-position quantities $H_q(\varphi)$ and $H_n(\varphi)$ which were obtained during the detection at the conductor $R$ are shown.
CHAPTER 9. ANALYSIS OF TECHNICAL OBJECTS

Figure 9.24: Phase-position quantities $H_{0n}(\varphi)$ and $H_n(\varphi)$ obtained at conductor $S$ and processed during a 5 minutes test on 10kV 3-core belted PVC cable at a test voltage of 5kV.

Figure 9.25: Statistical operators for the phase-position quantities $H_{0n}(\varphi)$ and $H_n(\varphi)$ shown in figure 9.24.

Figure 9.26: Recognition rate obtained for the test at conductor $S$ of the 10kV 3-core PVC cable.
9.4. 3-CORE BELTED PVC 10KV CABLE

Figure 9.27: Phase-position quantities $H_{q\theta}(\varphi)$ and $H_n(\varphi)$ obtained at conductor $T$ and processed during a 5 minutes test on the 10kV 3-core belted PVC cable at a test voltage of 5kV.

Figure 9.28: Statistical operators for the phase-position quantities $H_{q\theta}(\varphi)$ and $H_n(\varphi)$ shown in figure 9.27.

Figure 9.29: Recognition rate obtained for the test at conductor $T$ of the 10kV 3-core PVC cable.
Figure 9.30: Phase-position quantities $H_{q_n}(\varphi)$ and $H_n(\varphi)$ obtained at conductor $R$ and processed during a 5 minutes test on the 10kV 3-core belted PVC cable at a test voltage of 5kV.

Figure 9.31: Statistical operators for the phase-position quantities $H_{q_n}(\varphi)$ and $H_n(\varphi)$ shown in figure 9.30.

Figure 9.32: Recognition rate obtained for the test at conductor $R$ of the 10kV 3-core PVC cable.
The statistical operators for these distributions are shown in figure 9.31. The highest value of the recognition rate shows an "dielectric-bounded cavity". Here the origin of the discharges reveals a cavity or cavities between the core \( R \) and the sheath, see figure 9.32. The second highest recognition rate indicates an "electrode-bounded cavity". This may be correlated to a cavity or cavities where the insulation has been loosened from conductor \( R \). Apparently the handling of the cable has caused a defect in the region of core \( R \) of a type that can be recognized by this analysis.

9.5 150 kV Bushing

![Diagram of 150 kV Bushing](image)

**Figure 9.33:** Cross-section of the 150kV bushing with indication of possible discharge sites.

Tests have been made at 150kV capacitance graded bushing. This object, for a phase to earth voltage of 90kV, is composed of oil-impregnated paper inside a porcelain insulator, see figure 9.33. To obtain an optimal field distribution floating foils are inserted in the insulation.

Characteristic for this type bushings is their relatively low capacitance, in range of 10 to 20pF. If during an overvoltage test the
capacitance increases it could be mean that short circuits occur be-
tween the floating foils. At a bushing, that was rejected for this
reason discharge measurements were carried out. In figure 9.34 a
photograph of the bushing is shown.

![Figure 9.34: Photograph of 150kV bushings. The bushing under test is the upper one.](image)

The inception of discharges was found at a voltage of 80kV r.m.s. Ul-
trasonic detection confirmed that the discharges were located inside
the bushing.

For measuring purposes, this capacitance graded bushing has a tapp-
ing on the outer floating foil. Using this tapping for the straight
detection circuit, the bushing was subjected to a 90kV r.m.s. test
voltage throughout 20 minutes (test A).

In figure 9.35 the phase-position quantities $H_qn(\varphi)$ and $H_n(\varphi)$ are
shown.

The statistical operators processed for these distributions are shown
in figure 9.36.

Analysis with the aid of the recognition rate is not as clear as in the
9.5. 150 KV BUSHING

**Figure 9.35:** Phase-position quantities $H_{\text{eq}}(\varphi)$ and $H_n(\varphi)$ processed during a 20 minutes test on the 150 kV bushing of figure 9.34 at a test voltage of 90kV r.m.s.

**Figure 9.36:** Statistical operators for the phase-position quantities $H_{\text{eq}}(\varphi)$ and $H_n(\varphi)$ shown in figure 9.34.

**Figure 9.37:** Recognition rate obtained for the test on the 150kV bushing tested at 90kV r.m.s.
preceding cases. It appears that the cases "the electrode-bounded cavity", "the dielectric- bounded cavity" and "the flat cavity", have a significantly higher recognition rate than the other defects, see figure 9.37. Based on the fact that, to discriminate between electrode- and dielectric bounded cavity a flat one was studied in section 7.2, the conclusion may be drawn that a flat cavity is discharging between the foils or adjacent to a foil.

![Figure 9.38: Maximum discharge magnitude $q_{\text{max}}(t)$ observed during a test at 90kV r.m.s. when after 10 minutes the pressure at the oil condenser was increased from atmospheric pressure to 5 bar.](image)

To confirm this indication, the oil pressure was varied. An another 20 minutes test at 90kV r.m.s. was carried out. After 10 minutes of discharging, the oil condenser was put at a pressure of 5 bar. In figure 9.38 the behaviour of the maximum discharge magnitude $q_{\text{max}}(t)$ is given. This quantity shows that after 12 minutes the discharges are disappeared. After this handling and after the removing of the pressure at the oil condenser, the inception of discharges appeared to be permanently increased to the range of 140kV r.m.s. This change in the discharge inception may be correlated to the changes in the geometry of the defect.

Next, the second 20 minutes test was made (test B) at a voltage level of 160kV r.m.s. In figure 9.39 the phase-position quantities the $H_{\varphi n}(\varphi)$ and $H_n(\varphi)$ are shown.
The statistical operators processed for these distributions are shown in figure 9.40.

**Figure 9.39:** Phase-position quantities $H_{q\varphi}(\varphi)$ and $H_{n}(\varphi)$ processed during a 20 minutes test on the 150 kV bushing at a test voltage of 160kV r.m.s.

**Figure 9.40:** Statistical operators for the phase-position quantities $H_{q\varphi}(\varphi)$ and $H_{n}(\varphi)$ shown in figure 9.39.

The *recognition rate* for these statistical operators shows the highest value at the defect "square cavity". Also "electrode- bounded cavity", "dielectric- bounded cavity" and "flat cavity" have significant higher recognition rate in contrast to other defects, see figure 9.41. The comparison of the recognition rates of both tests (A) and (B), see figures 7.37 and 7.41 provides the presumption that due to moving of the oil under the pressure the flat cavity in (A) has become a
square one in test (B) resulting in higher inception voltage. The relative lack of recognition in these results can possibly be related to the fact that no voids in paper were studied in the 15 physical models, which are used here as a comparison.

9.6 Conclusions on technical objects

Tests on various actual objects have led to the following conclusions:

1. The \textit{statistical response} obtained from tests on 15 different physical models may be used to analyze data obtained on actual objects.

2. The origin of discharges in actual objects could be traced back.

3. The system of 15 physical models shall be extended with defects in a three core configuration and with defects in oil impregnated paper insulation.

4. It is advisable to study combinations of different defects in physical models.
Chapter 10
Conclusions and suggestions

CONCLUSIONS

1. Each discharge source, differing in geometry, location in the insulation, type of dielectric and applied field, is characterized by time behaviour in the discharge process.

2. Because of this time behaviour, it is useful to determine deduced quantities on the basis of three independent quantities: the apparent charge $q_i$, the phase angle $\varphi_i$ of a discharge, and the ignition voltage $U_i$.

3. For analysis purposes, over 20 deduced quantities are at our disposal. In this thesis 5 deduced quantities have been studied: three quantities as a function of time and two quantities as a function of the phase angle.

4. The distributions of the quantities as a function of the phase angle provide valuable information about the discharge source. The number of observed discharges as a function of the phase angle $H_n(\varphi)$ and the average discharge amplitude as a function of the phase angle $H_{qn}(\varphi)$ were chosen for further study. Both distributions are separately observed at the positive and the negative half of the voltage cycle. The shape of the ensuring four distributions is correlated to different types of discharges.

5. The shape of $H_{qn}(\varphi)$ and $H_n(\varphi)$ distributions are described by statistical operators. Operators such as skewness, kurtosis, cross-correlation factor, etc. have been chosen for this purpose.

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6. The combination of 15 of these statistical operators forms the *statistical response* which can discriminate between different kinds of defects and can constitute a "finger print" of a discharge.

7. The changes in the defect under the influence of partial discharges, may be correlated to the changes in these operators. In particular initiation and growth of treeing is correlated to changes in the statistical operator: skewness of \( H_{q_n}(\varphi) \).

8. A number of physical models with known discharge source were built and were analyzed. Their statistical operators were determined and the scatter in this observations was recorded.

9. An unknown discharge source in an arbitrary sample can be compared with these models by using a simple algorithm called the *recognition rate*, which reveals the origin of discharges in an actual object.

10. The results have shown that a computer-aided discharge analysis enables the recognition of a discharge source in the case of 15 physical models. In the actual objects presented in chapter 9, this analysis has been affirmed.

It has been shown that computer-aided recognition of discharging defects can be effected in this way.

**SUGGESTIONS FOR FURTHER STUDY**

Based on these results, and using these analytical tools, it may be possible to improve this system for the diagnosis of defects in insulating systems. To this end some supplementary further studies are recommended below.

The analyzer has been built which processes discharge signals according to the rules stated above. This analyzer enables the following studies:

1. Enlarging the data base by analyzing more physical models.
2. Gaining experience with a great variety of actual H.V. specimens.

3. Studying the effect of the following factors:

- the shape of the supply voltage
- the bandwidth of the discharge detector
- the signal dynamics above system noise
- the measuring time

4. Studying the ability to test more than one discharge source in one sample. The following aims are important:

- recognition of the occurrence of multiple defects
- recognition if possible, of the individual defects

The following other subjects can be studied when the above stated processing technique is changed:

1. Analyzing deduced quantities and statistical operators as a function of time.

2. Processing deduced quantities and statistical operators as a function of voltage when making step-up test.

3. Is better recognition made possible by using more or less than the processed operators?

4. It would be worth while to study other recognition tools than the present recognition rate.

5. Is statistical recognition possible for discharges at d.c. voltage?

6. Can the system be used at higher frequencies of the supply voltage, e.g. at 25kHz?
List of symbols

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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<tr>
<td>$B_m$</td>
<td>The capacity of the buffer memory in the acquisition unit</td>
</tr>
<tr>
<td>$C_{2.5%/97.5%}$</td>
<td>Quartiles of the 95% confidence interval covering the mean values $M_{so}$ of a number of observations. These quartiles are called limits of the statistical response, see equation (4.1)</td>
</tr>
<tr>
<td>$cc$</td>
<td>One of the statistical operators: the cross-correlation factor, see equation (2.17)</td>
</tr>
<tr>
<td>$D_n$</td>
<td>The noise suppression factor which represents the threshold value: only signals above this value are analyzed, see figure 8.1</td>
</tr>
<tr>
<td>$\Delta_{op}$</td>
<td>The recognition distance representing the smallest difference with the next best recognition rate, see figure 8.10</td>
</tr>
<tr>
<td>$\Delta V$</td>
<td>The voltage drop across a defect, see figure 2.1</td>
</tr>
<tr>
<td>$\Delta p_i$</td>
<td>The energy which is dissipated by a discharge, see equation (2.3)</td>
</tr>
<tr>
<td>$F_{ps}$</td>
<td>The permissible sampling frequency to register at least one period of 20ms of the discharge sequence, see equation (3.6)</td>
</tr>
<tr>
<td>$F_s$</td>
<td>The sampling frequency of the acquisition unit</td>
</tr>
<tr>
<td>$F_z$</td>
<td>Memory page; 108 kbyte memory for the storage of deduced quantities as a function of time, see figure 3.3</td>
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\( \Phi \)

A statistical operator: the phase asymmetry, see equation (2.16)

\( \varphi_i \)

Phase angle \((0 - 360^\circ)\) related to the moment of discharging

\( \varphi_{inc}^\pm \)

The inception phase angle in the positive or in the negative half of the voltage cycle

\( \varphi_t \)

Triggering moment for the data acquisition unit related to the test voltage

\( H_0 \)

Hypothesis in the nonparametric Kolmogorov-Smirnov test

\( H(q) \)

One of the deduced quantities: the distribution function of the discharge magnitude

\( H(p) \)

A deduced quantity: the distribution function of the discharge energy magnitude

\( H_n(\varphi) \)

A deduced quantity: the pulse count distribution, which represents the number of observed discharges in each phase window as a function of the phase angle.

\( H_{qm}(\varphi) \)

A deduced quantity: the maximum pulse height distribution, which represents the maximum value of discharges observed in each phase window as a function of the phase angle

\( H_{qn}(\varphi) \)

A deduced quantity: the mean pulse height distribution, which represents the average amplitude in each phase window as a function of the phase angle

\( H_{qs}(\varphi) \)

A deduced quantity: the discharge amount distribution, which represents the sum of the discharge magnitudes in each phase window as a function of the phase angle
LIST OF SYMBOLS

$H_n^\pm(\varphi)$: A deduced quantity: the pulse count distribution observed in the positive or in the negative half of the voltage cycle.

$H_{qn}^\pm(\varphi)$: A deduced quantity: the mean pulse height distribution observed in the positive or in the negative half of the voltage cycle.

$H_x$: Memory page; 24 kbyte memory for the storage of the distributions of the deduced quantities, see figure 3.3.

$i_q(t)$: Discharge current in the leads of the samples, see figure 2.2.

$Ku$: A statistical operator: the kurtosis, see equation (2.13).

$mcc$: A statistical operator: the modified cross-correlation factor, see equation (2.18).

$M_c$: The available memory capacity of the computer.

$M_p$: The energy resolution factor, representing the smallest detectable difference in energy magnitude, see equation (3.3).

$M_{so}$: Arithmetic mean of the values of a statistical operator obtained from a series of $N$ observations for one type of defect.

$M_q$: The discharge resolution factor, representing the smallest detectable difference in discharge magnitude, see equation (3.1).

$M_v$: The voltage resolution factor representing the smallest detectable difference in voltage magnitude, see equation (3.2).
LIST OF SYMBOLS

\( n \)  
The number of discharges observed in one phase window

\( N \)  
Number of observations for one type of defect

\( N_c \)  
The number of cycles 50Hz, alternatively 60Hz, registered during the transfer intervals \( T_m \), see equation (3.5)

\( N_q \)  
One of the basic quantities: number of discharges observed during a half voltage cycle

\( N_q(t) \)  
A deduced quantity: number of discharges processed during the test time \( T_T \); either for the positive half or for the negative half of the voltage cycle

\( p_{\text{max}} \)  
A basic quantity: maximum discharge energy observed during a half voltage cycle

\( p_{\text{max}}(t) \)  
A deduced quantity: maximum discharge energy magnitude processed during the test time \( T_T \); either for the positive half or for the negative half of the voltage cycle

\( p_{\text{mean}} \)  
A basic quantity: mean discharge energy observed during a half voltage cycle

\( p_{\text{mean}}(t) \)  
A deduced quantity: mean discharge energy magnitude processed during the test time \( T_T \); either for the positive half or for the negative half of the voltage cycle

\( P_e \)  
A statistical operator: number of peaks, see equation (2.19)

\( p_i \)  
A basic quantity: the energy that is supplied from outside during one discharge, see equation (2.2)
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$s$</td>
<td>Standard deviation of a series of $N$ observations of one type of defect</td>
</tr>
<tr>
<td>$Q$</td>
<td>A <em>statistical operator</em>: discharge asymmetry, see equation (2.14)</td>
</tr>
<tr>
<td>$q_i$</td>
<td>A <em>basic quantity</em>: apparent charge; the charge, which is displaced in the leads of a sample, see equation (2.1)</td>
</tr>
<tr>
<td>$q_k$</td>
<td>Discharge magnitude for the calibration of measured signals</td>
</tr>
<tr>
<td>$q_m$</td>
<td>The maximum value of the discharges observed in one phase window</td>
</tr>
<tr>
<td>$q_{max}$</td>
<td>A <em>basic quantity</em>: the maximum discharge magnitude observed during a half voltage cycle</td>
</tr>
<tr>
<td>$q_{max}(t)$</td>
<td>A <em>deduced quantity</em>: the maximum discharge magnitude processed during the test time $T_T$; either for the positive half or for the negative half of the voltage cycle</td>
</tr>
<tr>
<td>$q_{mean}$</td>
<td>A <em>basic quantity</em>: the mean discharge magnitude observed during a half voltage cycle</td>
</tr>
<tr>
<td>$q_{mean}(t)$</td>
<td>A <em>deduced quantity</em>: the mean discharge magnitude processed during the test time $T_T$; either for the positive half or for the negative half of the voltage cycle</td>
</tr>
<tr>
<td>$q_n$</td>
<td>The average value of discharges observed in one phase window</td>
</tr>
<tr>
<td>$Q_N$</td>
<td>An inventory of basic and deduced quantities to be processed during the test</td>
</tr>
<tr>
<td>$q_s$</td>
<td>The sum of the discharge magnitudes observed in one phase window</td>
</tr>
</tbody>
</table>
LIST OF SYMBOLS

\( Q_s \)  
A basic quantity: the integrated discharge magnitude observed during a half voltage cycle, see figure 2.2

\( Q_s(t) \)  
A deduced quantity: the integrated discharge magnitude processed during the test time \( T_T \); either for the positive half or for the negative half of the voltage cycle

\( R \)  
Reduction factor; the number of cycles representing in one cycle

\( Sk \)  
A statistical operator: the skewness, see equation (2.12)

\( Sk(t) \)  
A statistical operator: the time behaviour of skewness \( Sk \)

\( S_{min,max} \)  
The minimal and maximal discharge measured, see equations (4.2) and (4.3)

\( t \)  
A statistical test parameter depending on the probability and the number of observations \( N \) (\( t \)-distribution)

\( T_c \)  
Duration of the test, expressed in the number of 50 (60)Hz cycles in the case of short test periods

\( T_m \)  
The length of the transfer interval, see equation (3.4)

\( T_T \)  
Duration of the test expressed in minutes in the case of longer test periods

\( U^\pm \)  
Ignition voltage: voltage over the defect (or in general over the discharge path) at which the cavity breaks down, see figure 2.1

\( U_{term} \)  
A basic quantity: the terminating voltage, the voltage at the sample at which discharge pattern in a half cycle terminates, see figure 2.2
LIST OF SYMBOLS

\( U_{\text{term}}(t) \)  
A deduced quantity: the terminating voltage processed during the test time \( T_T \); either for the positive half or for the negative half of the voltage cycle

\( U_i \)  
A basic quantity: the momentary value of the test voltage \( V_a \) at the moment of occurrence of a discharge, see figure 2.2

\( U_{\text{inc}} \)  
A basic quantity: the momentary inception voltage, voltage at the sample at which the discharge pattern of a half cycle starts, see figure 2.2

\( U_{\text{inc}}(t) \)  
A deduced quantity: the inception voltage processed during the test time \( T_T \); either for the positive half or for the negative half of the voltage cycle

\( V^\pm \)  
The voltage that remains over the cavity after breakdown, see figure 2.1

\( v_a \)  
Amplification rate of the discharge signal

\( V_a \)  
Test voltage over the sample, see figure 2.1

\( V_c \)  
Voltage over the defect, see figure 2.1

\( V_i \)  
Inception voltage: voltage over the sample at which the first discharges are observed if the voltage is increased

\( X_{\text{op}} \)  
Combination of 15 statistical operators processed for a discharge source

\( X_{\text{RAM}} \)  
The digitized memory value of \( q_k \) or \( V_k \)

\( W_s \)  
A basic quantity: the integrated discharge energy magnitude observed during a half voltage cycle, see figure 2.2
| $W_s(t)$ | A *deduced quantity*: the integrated discharge energy magnitude processed during the test time $T_T$; either for the positive half or for the negative half of the voltage cycle |
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In February 1990, the manufacturer of high-voltage equipment Emil Haefely α Co Ltd, Basel, Switzerland showed interest in the results presented in this thesis. Since then, a close cooperation has been realized. The main goal of this cooperation is to use the results presented in this thesis for developing a generally available detection system. A prototype of this discharge analyzer is expected to be ready in autumn 1991.
Samenvatting

Om de bedrijfszekerheid van hoogspanningsinstallaties te waarborgen wordt bij de kwaliteitscontrole van de isolatie ontladingsdetectie toegepast. In het bijzonder speelt het onderzoek naar de oorzaak van partiële ontladingen en het treffen van maatregelen om deze in de toekomst te voorkomen een essentiële rol. Om een uitspraak te kunnen doen over de aard van een partiële ontlading, hetgeen op zijn beurt informatie kan geven over het gevaar voor het dielectricum, is in loop van de jaren een herkenningsysteem van oscillografische ontladingspatronen ontwikkeld. Vaak zijn de werkelijke oscillogrammen van ontladingsbeelden moeilijk te evalueren doordat deze zijn opgebouwd uit bewegende en instabiele ontladingspulsen en niet direct met een gestileerd beeld corresponderen. De internationaal bestaande tendens tot het toepassen van digitale technieken concentreert zich op de verbetering van de evaluatie van ontladingspatronen door middel van geautomatiseerde registratie en analyse.

In dit proefschrift wordt de automatisering van conventionele ontladingsdetectie gebruikt voor het herkennen van verschillende ontladingsbronnen.

Hoofdstuk 1 geeft een algemene introductie.

Een specificatie van de geautomatiseerde ontladingsdetectie wordt gepresenteerd in hoofdstuk 2. Een studie van karakteristieke ontladingsgrootheden wordt gegeven in paragraaf 2.1. Uitgaande van beproevingssomstandigheden en meetprocedures voor conventionele ontladingsdetectie (bandbreedte van ca. 400 kHz) software en hardware elementen van een ontladingsanalysator worden behandeld in paragraaf 2.2.

In hoofdstuk 3 wordt de configuratie van ontladingsanalysator met de mogelijkheid van continue registratie van ontladingsgrootheden gepresenteerd.

In hoofdstukken 4, 5, 6 en 7 worden met deze analysator de fysische modellen van ontladingsbronnen in gassen, vloeistoffen en vaste ma-

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terialen onderzocht. Uit deze experimenten blijkt dat diverse bronnen door kenmerkende verschillen in het gedrag van de ontladingsgrootheden worden gekarakteriseerd. Niet alleen de basissgrootheden zoals ontladingsgrootte, onstekspanning, het aantal ontladingen en de fase positie, maar ook de afgeleide grootheden zoals de ontladingsintensiteit en de gemiddelde ontladingsgrootte als functie van de fasehoek vertonen een onderscheidend vermogen. Een belangrijk stap voor de evaluatie van deze metingen wordt gedaan door deze ontladingsgrootheden met statistische operatoren zoals skewness, kurtosis, kruisscorrelatie factor etc. te analyseren.

In hoofdstuk 8 wordt voor de herkenning van verschillende soorten defecten een systematiek van statistische operatoren opgebouwd.

In hoofdstuk 9 werd de boven gepresenteerde analytische methode toegepast op industriële hoogspanningsobjecten. De resultaten van deze metingen worden geanalyseerd met een eenvoudig algoritme, genaamd *recognition rate*. Met behulp van deze analyse blijkt de oorzaak van de ontladingen in deze objecten aangewezen te kunnen worden.
Curriculum vitae

Edward Gulski was born in Włocławek, Poland, on July 31, 1958. After graduating in 1977 from the Lyceum Ziemi Kujawskiej in Włocławek, he studied at the Faculty of Electrical Engineering at the Technical University Dresden, Germany, where he graduated in February 1982.

From March 1982 until July 1986, he worked as a research assistant at the High Voltage Laboratory of the same university. He was engaged in partial discharge measurements and dielectric diagnostics. In July 1986 he emigrated to the Netherlands.

From August 1986 until March 1987 he joined the Instrument Factory P.L. Komin B.V. in IJpendam, the Netherlands. In April 1987 he joined the High Voltage Laboratory of the Delft University of Technology, where he performed research in the field of diagnostics in high-voltage systems leading to this Ph.D. thesis.