Partial Discharges at dc Voltage: Their Mechanism, Detection and Analysis

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ABSTRACT

A concise review is given of the progress made in the field of partial discharges (PD) at dc voltage. Although ample reference will be made to work of other authors in this field, the paper will concentrate on the progress that was made at Delft University of Technology over a period of 14 years in three Ph.D. projects. In the first project, a start was made with the analysis of the physics of partial discharges at dc voltage and different types of PD were characterized based on parameters like time interval between PD and PD magnitude. In a second project, PD analysis was applied to HVDC apparatus and different means of classification of PD at dc voltage were proposed. In the third project, PD analysis was applied to HVDC mass-impregnated cables and test specifications were proposed. In this paper the work performed in the above three Ph.D. projects is summarized with ample reference to papers of other workers in this field. Attention is given to the mechanism of PD at dc voltage as compared to ac voltage and techniques for measurement and analysis of dc PD patterns. Examples of practical application of dc PD testing are given. Finally, some thoughts on future work are presented.

Index Terms — **dc voltage, partial discharge, detection, analysis, high voltage.**

1 INTRODUCTION

When one speaks of partial discharge it is in most cases assumed that we address PD at ac voltage. Without any doubt, the majority of the work on PD has always been focused on ac applications for the electrical energy supply. A thorough review of PD occurring at ac voltage was recently published by Bartnikas [1]. In the present paper we address the specific field of PD at dc voltage, which needs a special approach for a number of reasons. When we identify the type of applications that make use of a dc voltage we may draw the conclusion that apart from the high voltage dc (HVDC) transmission cable, most applications are found in sectors outside the electrical energy supply. Many everyday applications make use of HVDC, like CRTs for television and computer monitors but also automotive applications. In hospitals we find x-ray equipment and image intensifiers, in satellites traveling wave tubes are used for signal amplification, and radar is used both for civil and military applications.

In the literature PD at dc voltage are first mentioned, to the author's knowledge, in the sixties of the 20th century [2−8]. A good overview of the state of the art concerning PD at dc voltage halfway the 1970's was given by Densley in [9].

If we focus on the PD process itself, on the way PD at dc voltage is measured and interpreted and in the end may lead to a deterioration of the insulation we will note that we can not simply use our knowledge of PD at ac voltage. In fact, there is no hard evidence for a *direct* relation between PD at dc voltage and breakdown [10−12].

2.2 MECHANISM

Partial discharges in gaseous cavities inside a dielectric are usually considered the most dangerous. The mechanism of these so-called internal discharges is extensively described for instance in [13, 14]. Here, we present the treatment of internal discharges at dc voltage as was first described by Fromm in [15−19].

2.1 GENERAL

In order to start a PD, two conditions must be fulfilled. First, the magnitude and distribution of the electric field in the cavity should be such that a self-sustaining discharge can develop. This condition is generally translated into a minimum breakdown voltage V_{min} across the cavity. Second, a free electron must be present at a suitable posi-

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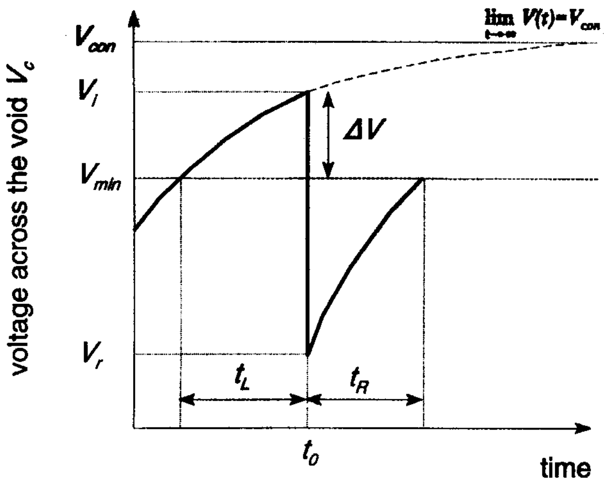

Figure 1. Voltage across a cavity in a solid dielectric [18].

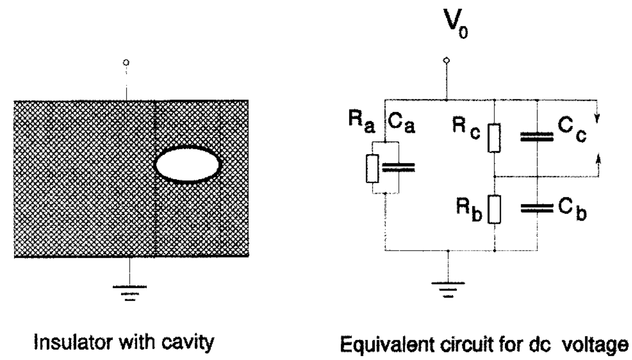

Figure 2. Equivalent model for a cavity discharge energized with dc voltage [18].

tion in the cavity to start the ionization process. This "starting" electron may be supplied by external sources (radiation), field emission or by detrapping of electrons deposited at the cavity walls by previous PD activity. The appearance of a starting electron is a stochastic process and is governed by a statistical time lag t_L. During this time lag the voltage across the cavity may exceed V_{min} by an overvoltage ΔV and the PD ignites at a voltage $V_i = V_{min} + \Delta V$. In Figure 1 this process is schematically represented.

Due to the charge displacement by the PD the voltage across the cavity drops to a residual value V_R. In contrast to what is often assumed this value is not zero, in fact it may even be close to V_i. For a new discharge to develop, the voltage across the cavity must again exceed V_{min} in a "recovery" time t_R.

2.2 PHYSICAL MECHANISM OF PD

The discharge process is strongly affected by the overvoltage ΔV. At dc voltages, ΔV usually is considerably smaller than at ac voltage. Let us consider an example of a cavity in a dielectric. It is often convenient to make use of an equivalent circuit to make some calculations on the PD process. For this purpose we extend the often-used capacitive equivalent circuit with some resistive elements to account for the conduction processes. In Figure 2 such a circuit is shown where C_a and R_a represent the properties of the entire dielectric, C_b and R_b represent the properties of the part of the dielectric "in series" with the cavity, C_c is the capacitance of the cavity and R_c the cavity surface resistance.

The PD process is strongly simplified and taken into account by a spark gap S. Thus, the time constant for charging the cavity is calculated as:

$$\tau = \frac{R_b R_c (C_b + C_c)}{R_b + R_c} \tag{1}$$

The voltage across the cavity $V_c(t)$ is given by:

$$V_c(t) = V_{c,\infty} - (V_{c,\infty} - V_r)\exp\left(-\frac{t}{\tau}\right) \tag{2}$$

with $V_{c,\infty}$ the limit value of the voltage across the cavity if no PD would occur. $V_{c,\infty}$ can be expressed as:

$$V_{c,\infty} = V\frac{R_c}{R_b + R_c} \tag{3}$$

Devins [13] studied the effect of overvoltage on the discharge mechanism and introduced two PD mechanisms named 'Townsend-like' and 'streamer-like' in analogy with the Townsend and streamer breakdown mechanis ms. In [17] a study is presented on the effect of overvoltage on PD mechanism at dc voltage by time-resolved measurements of the PD current pulses. In Figure 3 a typical current pulse is shown that was obtained in a 0.3 mm thick polyethylene test specimen with a 0.1 mm thick cavity at low overvoltages.

This Townsend-like discharge is characterized by a relatively small pulse height and a large pulse width that increases with cavity thickness. Others [13, 20, 14] have found for PD at ac voltage the same relation between cavity thickness and pulse width. Sometimes this discharge type is also referred to as pseudo-glow type [1].

At higher over voltages another type of discharge pulse was found, see Figure 4. The mechanism is referred to as "streamerlike" and is characterized by a fast pulse rise time and a short tail which reflect the strong ionization and the corresponding high electronic component in the discharge current [13, 14]. For further discussion of these mechanisms the reader is referred to [13, 14].

2.3 RECURRENCE OF PD

Recurrence of PD at ac voltage is easily explained by voltage polarity change every 10 ms (for 50 Hz supply), see Figure 5. At dc voltage, PD can recur because of the finite resistivity of the dielectric. After a PD, the next PD

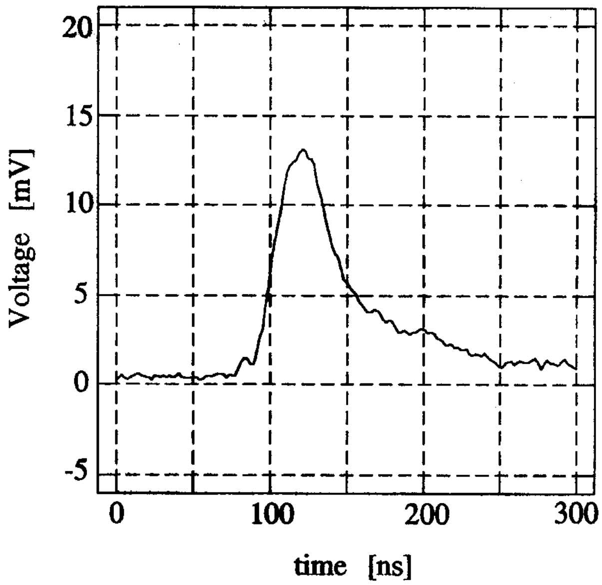

Figure 3. Townsend-like discharge pulse in a 0.1 mm cavity [18].

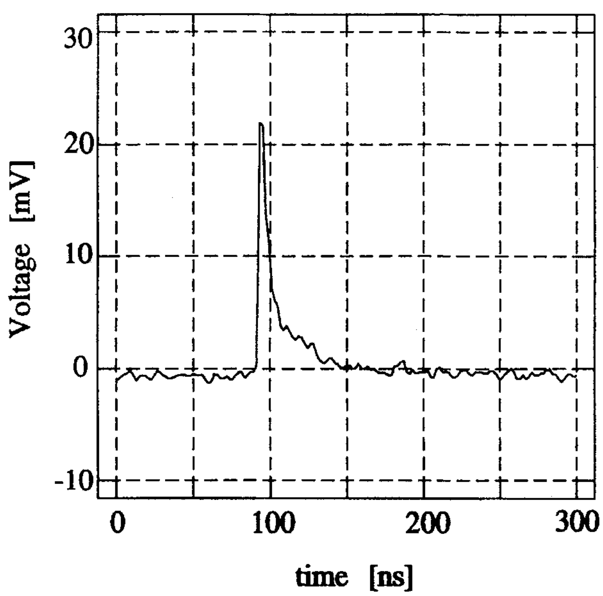

Figure 4. Streamer-like discharge pulse in a 0.1 mm cavity [18].

event can take place after a time interval Δt which is the sum of the recovery time and the time lag. The discharge repetition rate n is the reciprocal value of Δt, or

$$n = \frac{1}{\Delta t} \tag{4}$$

To obtain the maximum value of the repetition rate, we neglect the time lag, or $t_L = 0$.
Then we can derive the following relation:

$$\Delta t = t_R = -\tau \ln\left(\frac{V_{c,\infty} - V_{\min}}{V_{c,\infty} - V_r}\right) \tag{5}$$

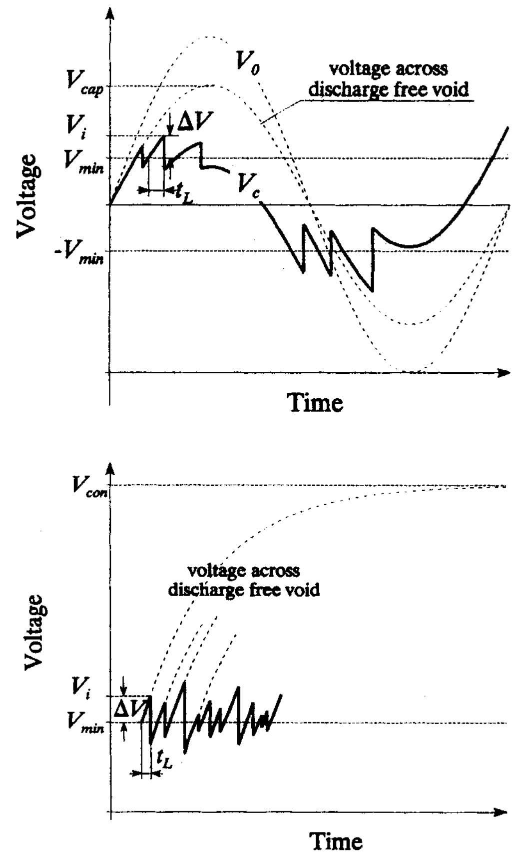

Figure 5. Recurrence of discharges at ac voltage (top) and at dc voltage (bottom) [12].

This is rewritten as:

$$\Delta\tau = -\tau \ln\left(1 - \frac{1}{\dfrac{V_{c,\infty} - V_r}{V_{\min} - V_r}}\right) \tag{6}$$

Assuming $V_{c,\infty} \gg V_r$ (which is generally true)

$$\Delta t \approx -\tau \ln\left(1 - \frac{1}{\dfrac{V_{c,\infty}}{V_{\min} - V_r}}\right) \tag{7}$$

Using a first order Tailor expansion we obtain:

$$\Delta t \approx \tau\left(\frac{V_{\min} - V_r}{V_{\mathrm{c},\infty}}\right) \tag{8}$$

Thus, the PD repetition rate equals:

$$n \approx \frac{1}{\tau}\left(\frac{V_{c,\infty}}{V_{\min} - V_r}\right) \tag{9}$$

The PD repetition rate is linearly proportional to $V_{c,\infty}$ which in turn is proportional to the external voltage.

This dependence has important consequences for the discharge inception voltage as it is detected in practice. At dc voltage, the discharge inception voltage recorded depends on the minimum value of the PD repetition rate that can be measured. In theory, the repetition rate just above inception is almost zero. Therefore, in practice the PD inception voltage is usually defined as the voltage at which the PD repetition rate is above 1 discharge per minute.

Let us now compare the PD repetition rates at dc and ac voltages with amplitude V.

For ac voltage it can be deduced that

$$n_{dc} \approx \frac{b}{c}\frac{dV}{dt}\frac{1}{V_{\min} - V_r} \tag{10}$$

For dc voltage

$$n_{dc} \approx \frac{1}{\tau}\frac{b}{c}\frac{V}{V_{\min} - V_r} \tag{11}$$

These repetition rates are equal if

$$\frac{dV}{dt} = \frac{V}{\tau}$$

Comparing the repetition rates at 50 Hz and dc, equality is reached when $\tau \approx 3$ ms. Because in practice τ is many orders of magnitude larger, the PD repetition rate at ac is orders of magnitude higher than at dc voltage with the same amplitude. There is one exception to this rule, i.e. relative high repetition rates can occur in dc insulation systems when the insulation is polarized or depolarized during respectively first application and turning off of the voltage.

2.4 TRANSIENT EFFECT OF INSULATION POLARIZATION

The distribution of the electric field at dc voltage is determined by the operating condition of the insulation system. When the voltage is applied the field is capacitively graded and only after all polarization processes have been completed the field is resistively graded. Further, the field distribution is affected by the load of the insulation system, i.e. conductor losses result in a temperature gradient which affects the insulation conductivity. In [21] a thorough treatment is given on the electric field distribution in HVDC cables at different operating conditions.

During polarization of the insulation when the voltage is switched on, an increased conductivity is observed which can be recognized in the polarization current. The PD repetition rate is high and follows closely the polarization current as was shown in [10, 11]. In Figure 6 this effect is clearly recognized in the strong increase of PD repetition rate just after the voltage across a test specimen was raised. When the voltage is switched off and the insulation is depolarized, PD of opposite polarity occur at a high repetition rate which may last for some time after the voltage has been turned off. This phenomenon is even enhanced at a polarity reversal.

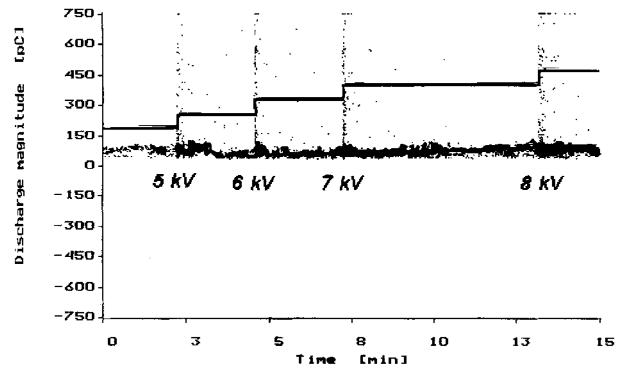

Figure 6. Partial discharge magnitude recorded during a stepwise increase of the test voltage.

2.5 EFFECT OF TEMPERATURE

In contrast to ac, the temperature and the temperature gradient across the insulation have a major as well as a complex influence on the PD behaviour.

The resistances shown in Figure 2, representing the resistances of dielectric and cavity, are strongly affected by temperature. The conductivity of a dielectric changes by orders of magnitude when the temperature of the insulation is raised from an ambient temperature of 20 °C to an operating temperature between 60 °C and 90 °C; see for paper-oil insulation [11] and for XLPE [22]. The PD repetition rate is directly affected by the increase in conductivity, i.e. an increase in conductivity by two orders of magnitude would result in a similar increase of the PD repetition rate [23]. In oil-paper insulation systems the effect of temperature is often twofold, i.e. an increase in temperature will result in an increase in conductivity and this in an increase of PD repetition rate but also in a transient redistribution of oil. The latter process may lead to the temporary formation of low density areas and a sharp increase in PD repetition rate [24]. This behavior is dealt with in more detail in section 4.2.

A temperature gradient in the insulation will lead to a redistribution of the electric field which may lead to a disappearance of PD at some locations and the inception of PD at other locations.

2.6 PD MAGNITUDE

At dc voltages often not only the PD repetition rate observed is much smaller than at ac voltage, the PD magnitude is also much smaller [8, 10, 19].

The PD magnitude is strongly correlated to the electric field in the cavity at the moment the initiatory electron appears and starts the discharge process. The over voltage

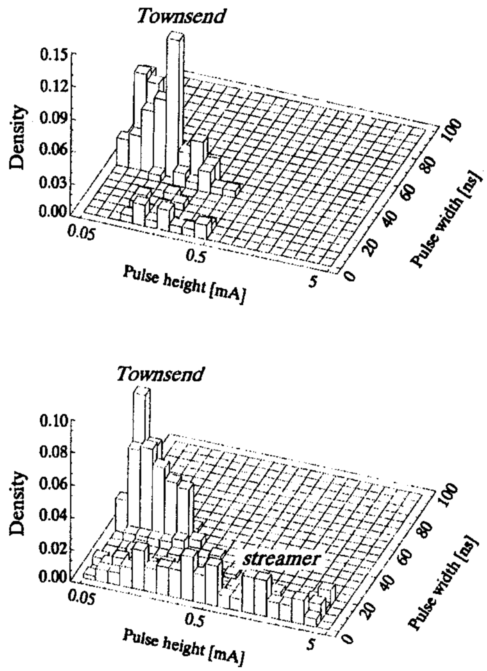

Figure 7. Top: Pulse width and pulse height distribution for discharges in a 0.1 mm cavity, 10 kV test voltage; Bottom: Pulse width and pulse height distribution for discharges in a 0.1 mm cavity, 20 kV test voltage [12].

at which a PD ignites thus has a direct effect on the PD magnitude. In [19], typical values of the over voltage were deduced from PD measurements on a test specimen consisting of 3 polyethylene (PE) sheets of 0.1 mm thickness with a 6 mm diameter hole in the centre sheet.

A value < 1.6 V was calculated which indeed is very small and due to the very slow rate of rise of the voltage across the cavity in relation to the average statistical time lag, i.e. $\tau \gg t_L$. In this study t_L was about 50 ms and τ was about 50 s. The resulting voltage drop after a PD had occurred was calculated to be 3.5 V which is very small if compared to the minimum breakdown voltage $V_{\min} = 980$ V determined by using Paschen law. In this case the ionization process in the cavity at PD inception is weak, in fact it is just strong enough to result in a self-sustained PD. The result is that the voltage across the cavity is stabilized by the PD of small magnitude to a value very close to $V_{\min}$. The value of the test voltage has an effect on both the predominating discharge mechanism and the discharge magnitude. In Figure 7, density histograms are shown for the above-mentioned specimens with pulse height and pulse width along the axes. A doubling of the test voltage resulted in an increase of the PD pulse height and in a change of the predominant PD mechanism from Townsend-like to streamer-like, all of which is explained by an increase of the over voltage at discharge ignition.

Only in the case of transient conditions, i.e. when raising the test voltage to its final value or switching off the voltage, the rate of rise of the voltage across the cavity is such that much higher over voltages may occur at PD ignition, resulting in PD magnitudes comparable to the ac case (Figure 6). This occurs, for instance, in a mass-impregnated HVDC cable that is energized (section 4).

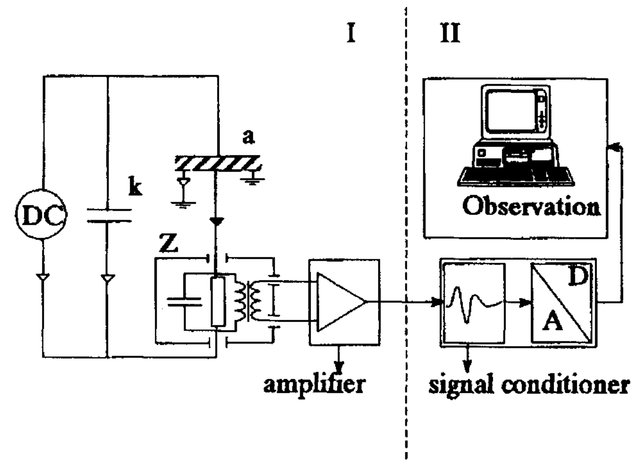

Figure 8. Partial discharge detection circuit used for dc. Part I is identical to the circuitry used for AC detection. Part II is dedicated to dc detection [44].

3 DETECTION AND ANALYSIS

For the detection of PD at dc voltage no special facilities are needed and in principle any ac PD test system can be used. Depending on the objective, one may choose for the standard PD detection system according to IEC60270 in case of PD testing of high voltage equipment (Figure 8), or, in case of more fundamental studies one may resort to an ultra-wide band circuit to obtain the shape of the PD pulses [14].

Because the PD repetition rate at dc voltage is low, PD data are normally acquired within a time span of 30 − 60 minutes. Although the duration of the PD test is quite long the PD behavior is not affected by processes like changes of surface conductivity of cavity walls due to the accumulation of PD by-products. Only after much more prolonged PD activity (24 h [12]) changes are observed in the PD behavior.

3.1 NOISE REDUCTION

Because of the unipolar nature of the dc voltage, partial discharges occurring in an object under test will also be of unipolar polarity. Partial discharges occurring in the external circuit necessarily are of opposite polarity. This fact can be made to use when distinguishing between noise from outside the test object and PD inside [12].

3.2 ANALYSIS OF PD DATA

The challenge is how to analyze the observed PD signals. At ac voltage, the PD behavior is voltage phase related and more or less characteristic phase patterns are observed for different types of PD generating defects. At

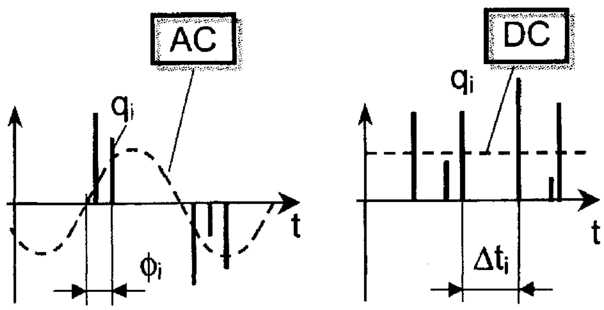

Figure 9. Basic PD parameters for ac (left) and dc (right) voltage [27].

dc voltage there is no generally accepted standard, different ways of representing the PD data have been proposed in literature.

Whatever the method of representation, there are only two basic parameters available, the discharge magnitude q_i and the time of occurrence t_i of the discharge (or the time Δt_i in between discharges). In Figure 9 a schematic representation is shown of the analogy between the basic parameters at ac and at dc voltage.

From a set of PD data (q_i, Δt_i) various graphical representations may be obtained. Again, the representation chosen depends on the application, whether it be the quest for more fundamental understanding, relatively simple go/no go testing in an acceptance test or extensive analysis of PD patterns in order to classify the type of defect. In the following sections typical examples will be given of each of these approaches.

3.2.1 PD MAGNITUDE AS A FUNCTION OF TIME: $q(t)$

This is the simplest way of representing the data and most often this is how the data is represented and initially evaluated during a PD test. In Figure 10 the $q(t)$ graph is shown for four different types of discharges, i.e. for PD in a dielectric bounded cavity, PD in oil, surface discharges

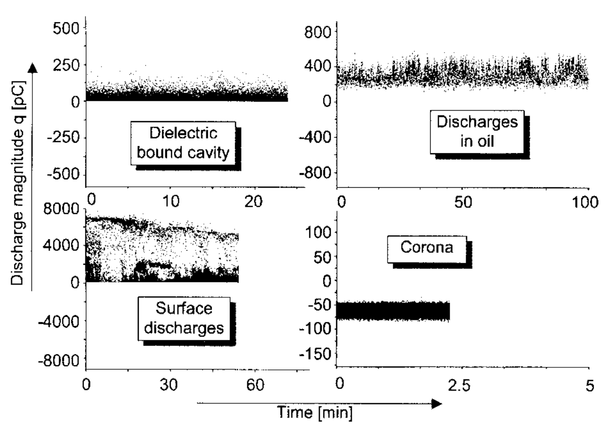

Figure 10. Plot of the discharge magnitude q against time for four different defects [27].

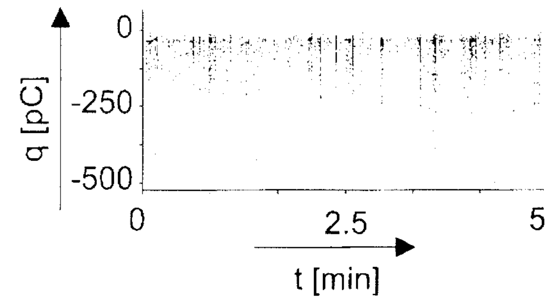

Figure 11. Discharge trains observed in oil [27].

and corona. From this figure, the erratic nature of surface discharges is clearly seen as opposed to the stable behavior of corona discharges.

The characteristic behavior of PD in oil. i.e. the occurrence of discharge “trains” [25] becomes clear when we zoom in to a shorter time interval as is shown in Figure 11.

3.2.2 DENSITY FUNCTION OF THE PD MAGNITUDE: $H(q)$

The density histogram of the PD magnitude is an often used representation of PD data [12, 6, 26]. In Figure 12 examples are shown of typical density functions for PD in a dielectric bounded cavity, PD in oil, surface discharges and corona. For cavity discharges the probability of occurrence decrease exponentially with the PD magnitude. Surface discharges are characterized by a large scatter in magnitude and corona shows the expected narrow distribution.

3.2.3 DISCHARGE MAGNITUDE AND REPETITION RATE AS A FUNCTION OF TEST VOLTAGE

Another, relatively simple, representation of the PD process is obtained when PD magnitude and/or PD repetition rates are plotted against test voltage. In Figure 13 examples of such plots are given for surface discharges and internal discharges. Because the volume to be discharged is restricted in the case of a cavity, (median) the PD magnitude is hardly affected in the voltage range that was used in this case. On the contrary, surface discharges show a strong correlation with test voltage because of the increase of the discharged area.

3.2.4 RELATION BETWEEN DISCHARGE MAGNITUDE AND AVERAGE MAGNITUDE OF ITS SUCCESSOR OR PREDECESSOR

There are more intricate ways of representing the PD behavior that shine some light on the relation or the absence thereof between consecutive discharges also referred to as memory effect [27]. In Figure 14 examples are

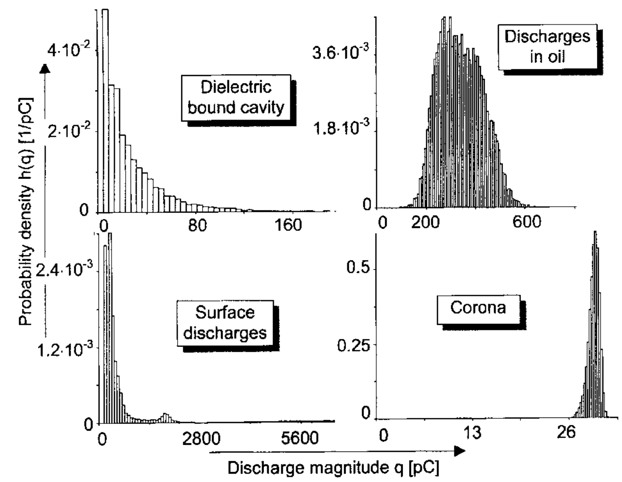

Figure 12. Characteristic PD probability density histograms for four model defects [27].

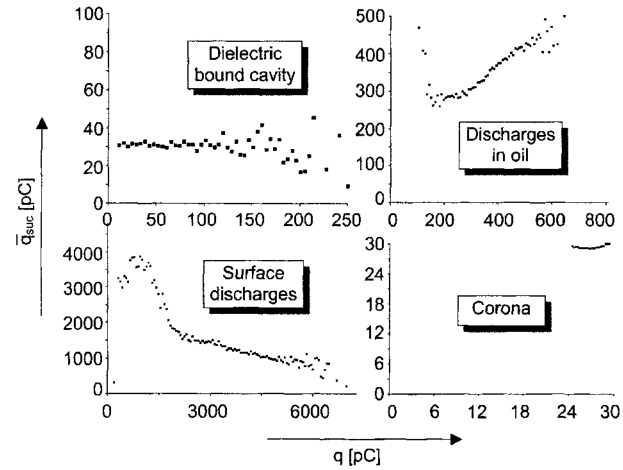

Figure 14. Characteristic graphs of the average magnitude of the successor discharge as a function of the discharge magnitude for four model defects [27].

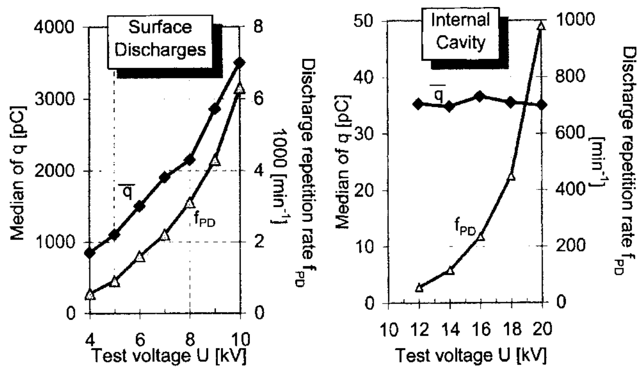

Figure 13. Discharge magnitude and repetition rate as a function of test voltage. Left: surface discharges; right: cavity discharges [27].

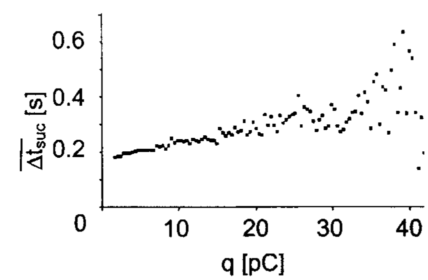

Figure 15. Average time to the successor for a given discharge magnitude in a cavity [27].

given of the relation between the magnitude of a discharge q and the average magnitude of its successor q_{suc}. The value of q_{suc} is calculated by averaging the successor discharges of all discharges q within a certain range (for instance $9 < q < 10$ pC). It can be deduced [18] that for PD in a cavity, $\bar{q}_{suc}$ is independent of q [12]. The same is true for corona discharges. Surface discharges and discharges in oil on the other hand show a negative, respectively positive correlation between q and $\bar{q}_{suc}$. The physical explanation for the absence or presence of such a correlation is described in [18, 27].

3.2.5 RELATION BETWEEN DISCHARGE MAGNITUDE AND AVERAGE TIME INTERVAL TO ITS SUCCESSOR OR PREDECESSOR

If, for a set of discharges the times to the successor or predecessor are averaged $\overline{\Delta t}_{pre} - q$ and $\overline{\Delta t}_{\text{suc}} - q$ graphs can be plotted. For discharges in a cavity it can be deduced that a positive correlation should exist between $\overline{\Delta t}_{\text{pre}}$ or $\overline{\Delta t}_{\text{suc}}$ and q [18]. In Figure 15 an example is given of such a plot for cavity discharges. For a positive correlation it is necessary that some assumptions be made regarding the physics of the PD process. The entire cavity is assumed to discharge and the discharge mechanism should be Townsend-like. In Figure 15 it is seen that for higher values of the PD magnitude the clear correlation disappears. This is explained by the fact that the larger discharges are frequently of the streamer-like type and thus not all requirements for a positive correlation are fulfilled. A full description of the physical background for this type of PD behavior can be found in [18, 12].

3.2.6 CUMULATIVE DISCHARGE REPETITION RATE AS A FUNCTION OF PD MAGNITUDE

This plot is obtained by plotting the cumulative discharge repetition rate for all $q \geq q_i$ against q_i. An example of such a plot is given in Figure 16. This type of representation is often used in combination with a test criterion, as will be explained in section 4.

3.3 MULTIPLE DEFECTS

The analysis in the section above was made for single defects and becomes much more complex in case multiple defects, possibly of a different nature are present. A dis-

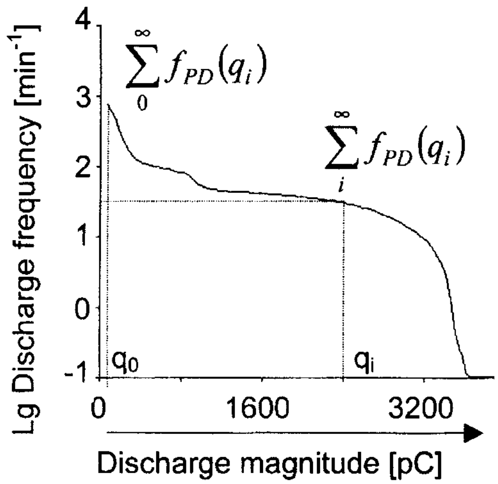

Figure 16. Graph of the cumulative discharge repetition rate [27].

tinction can be made between two or more sources of the same type discharging and two or more sources of two or more different types discharging.

If the sources have equal inception voltage, PD magnitude and equally shaped distributions, the source will be identified correctly. The number of sources cannot be determined. If the sources are of the same type but with unequal PD magnitude or inception voltage, they can be discriminated by raising carefully the test voltage.

If the sources are not the same, a correct identification can be made for instance when the PD magnitude density distributions do not entirely overlap. In such a case, the data of both distributions can be analyzed separately. In [28], it was shown that for an x-ray tube PD a distinction could be made between corona PD and PD in the bushing.

3.4 CLASSIFICATION OF PD DATA

For ac voltage, distributions and density functions of the basic parameters q and ϕ are used to describe and discriminate partial discharge patterns from various types of defects [29]. For dc voltage, the earlier introduced basic parameters q and Δt are used to build distributions and density functions [30–32]. The distributions shown in Figure 17 are created:

- $H_{q\ \max}(\Delta t_{pre})$ and $H_{q\ \max}(\Delta t_{suc})$, representing the maximum PD magnitude as a function of Δt_{pre} or Δt_{suc}.
- $H_{qn}(\Delta t_{pre})$ and $H_{qn}(\Delta t_{suc})$, representing the mean PD magnitude as a function of $\Delta t_{\rm pre}$ or Δt_{suc}.
- $H(q)$, the density function of the discharge magnitude.
- $H_n(\Delta t)$, representing the density function of the time between discharges Δt.

Each of the distributions in Figure 17 were found to have a characteristic shape [30–32, 27] that depends on the type of defect which generates the discharges. These shapes are described by a set of parameters quite similar

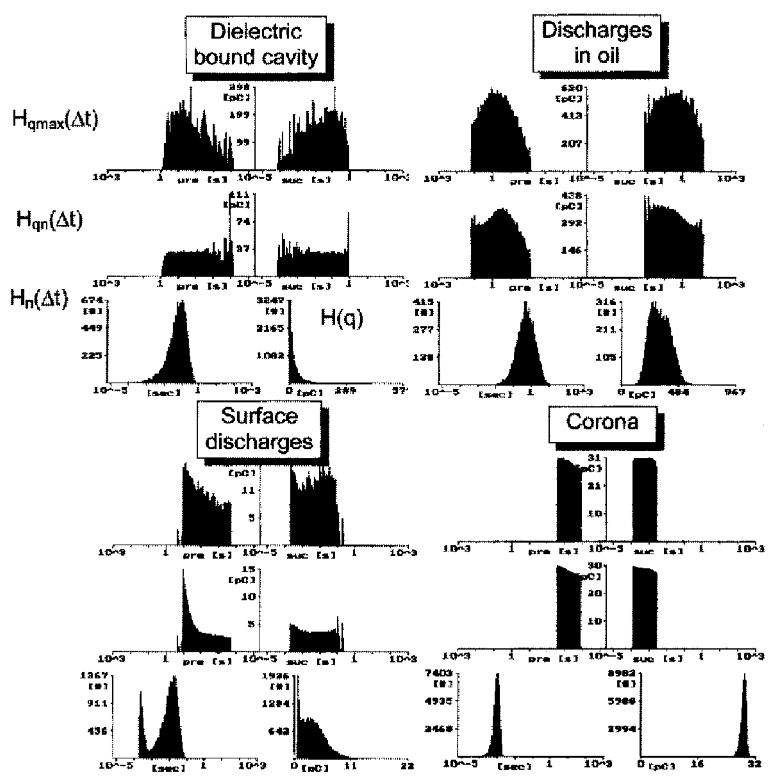

Figure 17. Examples of statistical distributions of four model defects used to construct a database for defect classification [27].

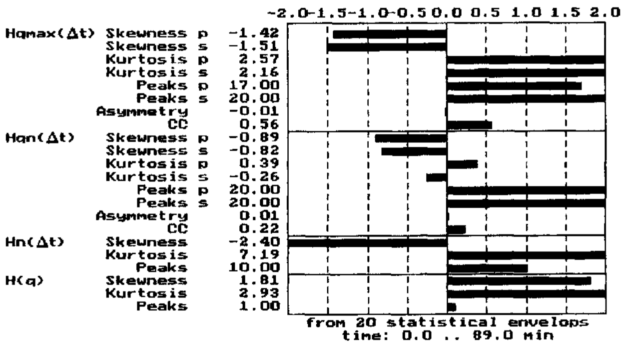

Figure 18. Fingerprint of a discharge [27].

to the ones that were used to describe ac partial discharge phase distributions. A set of in total 22 parameters is calculated and a "fingerprint" is obtained. Figure 18 shows the fingerprint of PD in a dielectric bound cavity of which the distributions are shown in Figure 17.

For classification purposes a database was built containing the fingerprints of a large number of known reference defects. Details on how such a database is constructed are given in [27].

To classify an unknown discharge source a comparison is made between its fingerprint and the fingerprints stored in a database of reference defects, using the Centour Score method [33].

For model defects tested in a laboratory surrounding this method proved to be quite powerful and the method was used with success to discriminate between different types of cavities, corona, surface discharges and discharges in oil. The first author of this paper is of the opinion that analysis of the PD data using the representations described in section 3.2 is to be preferred. An important advantage over an automatic classification procedure is the fact that the link with the physical processed is not lost.

4 PRACTICAL APPLICATION OF dc PD MEASUREMENTS

In a number of cases partial discharge measurements are successfully applied in dc apparatus. The first references to practical applications were made in the 1960s, primarily on paper-oil insulated systems, i.e. cables [2] and capacitors [7]. In 1970–1980, publications appeared on partial discharges in polyethylene submarine cable [34], aerospace applications [35–38] and traveling wave tubes [39]. In the 1980s, Delft University of Technology published its extensive work on dc partial discharge analysis and classification [12, 23, 28, 31, 32, 40–45,]. In the following, examples are given of practical applications of dc PD detection and analysis.

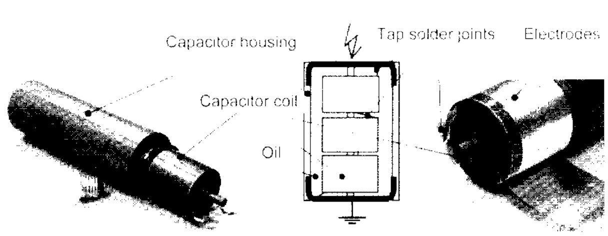

Figure 19. Paper impregnated HVDC capacitor 75 kV, 8 nF.

4.1 HVDC CAPACITORS

Capacitors are often applied in power supplies for X-ray equipment and electron microscope applications. The majority of these are still of the oil-paper type often in combination with layers of polypropylene. In [27], different classes of such capacitors were studied with respect to their partial discharge behavior and the possibilities of using PD measurements to distinguish bad products from good products. In Figure 19 an example of such a capacitor is shown.

It is important to note that all these capacitors are designed in such a way that some air accumulates above the top compartment to allow for some expansion of the oil. To prevent air bubbles getting into the electrically stressed areas of the capacitors they need to be installed and operated in a vertical position.

For all classes of capacitors a certain amount of partial discharge activity was observed at their rated voltage. In plots of $\bar{q}_{suc}$ or q_{pre} against q and $\overline{\Delta t}_{pre}$ or $\overline{\Delta t}_{suc}$ against q, no correlation is seen between these parameters; neither an erratic pattern is observed nor a constant value of the dependent quantity (Figure 20).

In order to find out if a predominant defect would be singled out by a PD test a small amount of air (about 1 ml) was allowed to enter one of the capacitors via the ground plate. The PD plots of this capacitor could be easily discerned from the others by the fact that a definite correlation was present between $\bar{q}_{suc}$ or $\bar{q}_{pre}$ against q and $\overline{\Delta t}_{pre}$ or $\overline{\Delta t}_{suc}$ against q, as is shown in Figures 21 and 22.

One of the conclusions of this work was that the existence of a potentially dangerous, predominant defect often leads to a clear correlation between the above discussed parameters. The type of correlation is given by the defect type and the physical mechanism of the discharge process [27].

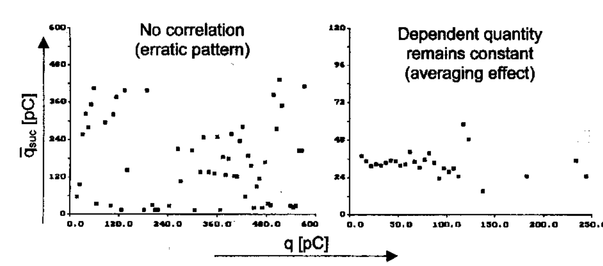

Figure 20. Typical correlation between PD parameters observed for healthy capacitors [27].

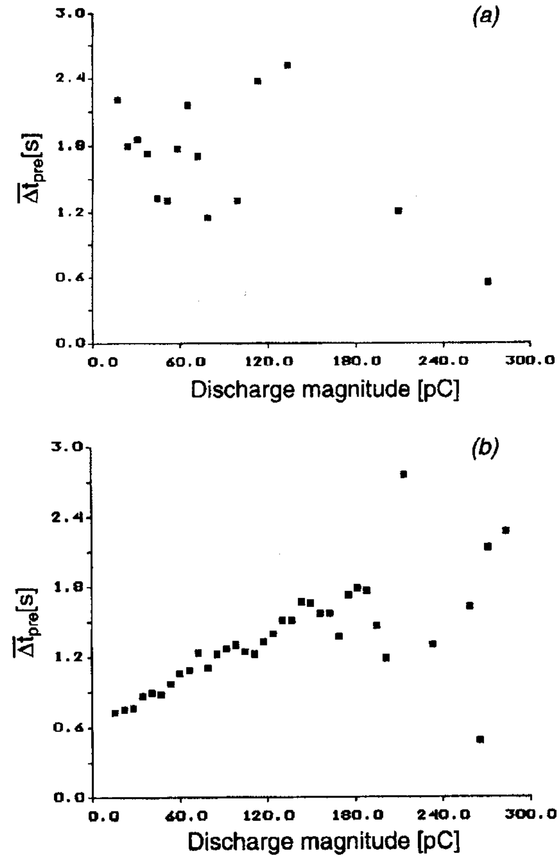

Figure 21. Top: pattern for a healthy capacitor; bottom: pattern for a capacitor in which a small amount of air was introduced [27].

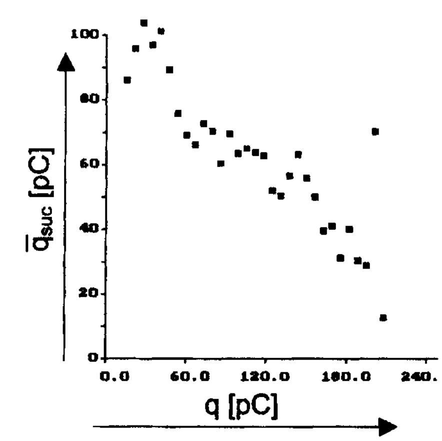

Figure 22. PD pattern for a capacitor in which a small amount of air was introduced [27].

Another, simpler, way to distinguish "healthy" capacitors from those with defects is the analysis of the plot of the cumulative discharge repetition rate for all $q \geq q_i$ against q_i. This method is relatively easy to implement in practice and gives a straight answer on the quality of the product. In Figure 23 a plot is shown of all classes of capacitors tested. To distinguish between a good and a bad product a criterion was defined, similar to the suggestions

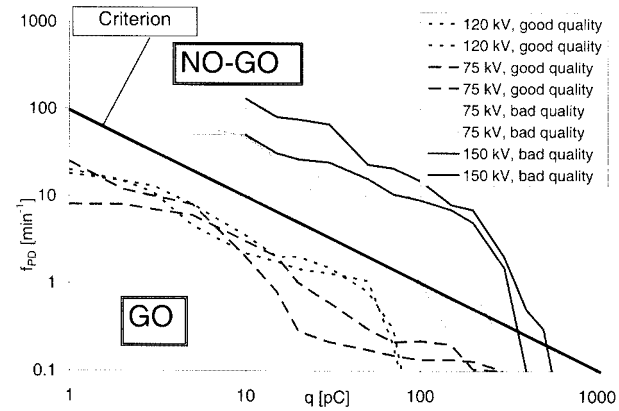

Figure 23. PD criterion for HVDC capacitors [27].

of Jeroense [44, 46] for HVDC cables. A cumulative PD product of 100 pC·min^{-1} is suggested for capacitors as a boundary between a GO and a NO-GO area. Because of the strong dependence of discharge repetition rate on temperature these tests need to be performed at a specific temperature, preferably the operating temperature. If a capacitor exceeds this limit, it is to be discarded.

This test criterion is tough in comparison to those given elsewhere. Kreuger suggested in [11] a criterion of 2 nC·min^{-1} for HVDC equipment though he also stated that the criterion might further be adjusted in as far as detailed information on the particular test object exists. More recently, Jeroense [44] suggested test criteria for HVDC cables; i.e. 500 pC·min^{-1} for type tests and 2 nC·min^{-1} for routine tests.

4.2 HVDC CABLES

The behavior of mass impregnated HVDC cables was studied and in particular the partial discharge behavior was observed during different operating conditions of the cable. By extensive PD analysis the behavior of the cable insulation could be described in detail.

In a HVDC cable system, the voltage and load current may vary and as a result the temperature distribution, the electric field, the internal pressure, the distribution of cavities in the cable, the viscosity of the oil and the conductivity of the insulation will change as well.

When the partial discharge repetition rate of such an HVDC cable is recorded during a typical load cycle of 8 h load on and 16 h load off, a pattern is found that is characteristic for this type of cable insulation (Figure 24). Initially, the temperature of the cable is still rising and a thermal equilibrium is arrived at after approximately 8 h. In [44] it is shown that there are three competing processes that affect the PD repetition rate in this first stage; the changing distribution of the electric field in relation to the position of the cavities, the decrease of the relaxation time constant due to the increased insulation conductivity

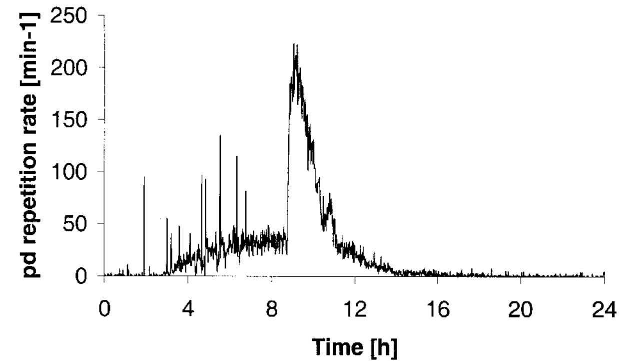

Figure 24. Characteristic behavior of the PD repetition rate in a mass impregnated cable during a load cycle.

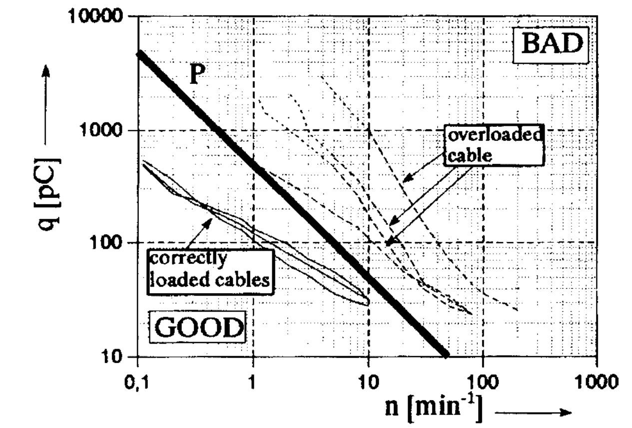

Figure 25. PD criterion for HVDC mass impregnated cables; type test [44].

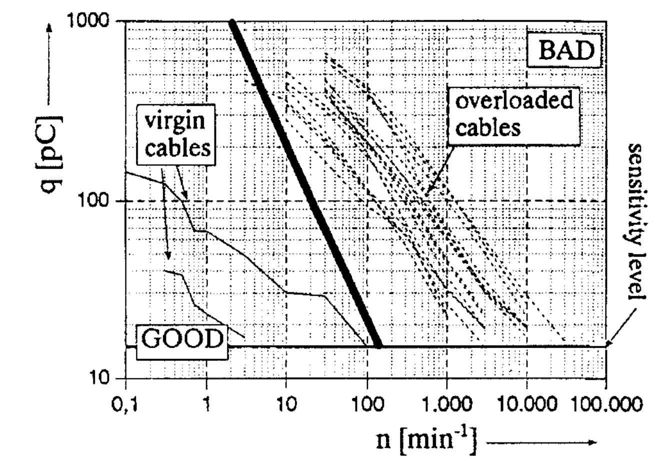

Figure 26. PD criterion for HVDC mass impregnated cables; routine test [44].

and the changing distribution of voids through the insulation due to the expansion of oil. The decrease of the relaxation time constant most often is seen to be dominant, resulting in an increase of PD repetition rate. After 8 h the load is switched off and a remarkable peak is seen in the PD repetition rate. This behavior has been studied extensively by Jeroense [44] and later by Evenset [47, 48] and explained as being the result of a sudden pressure change in the cable insulation [49] as a result of which cavities are generated. Normally, at nominal operating conditions, the PD repetition rate returns to a low value of about 1 discharge per minute after the load cycle has been completed.

When a mass impregnated cable is overloaded or otherwise the cable insulation is highly overstressed, the population of cavities in the insulation may be irreversibly changed. In [45] a series of ac medium voltage mass impregnated cables at different voltages up to 7 times the nominal voltage. It was observed that above a certain threshold voltage the cavity population started to grow which was reflected in the increase of the PD repetition rate after consecutive load cycles.

For type tests he suggested to perform PD measurements during the entire stability test, but in particular during the first hours after switching off the load when most harmful PD occur. A cumulative PD product of 500 $pC \cdot min^{-1}$ was suggested which was based partly on recommendations by Kreuger [11] and on the results of a set of experiments on correctly loaded and heavily overloaded cables (Figure 25). The overloaded cables did not pass a shortened type test according to the Electra 72 document [50].

For routine tests, Jeroense proposed to perform PD measurements after switching off the test voltage. As a result of the decreasing voltage a relatively high repetition rate is detected which facilitates the PD measurement and allows a discrimination between good and bad cables, as is shown in Figure 26. In this case a cumulative PD product of 2 $nC \cdot min^{-1}$ was suggested.

5 CONCLUSIONS

In this paper a concise overview was given of the work on partial discharge measurement and analysis at dc voltage, in particular the work that was done at Delft University of Technology. From this work the following may be concluded:

Partial discharge activity at dc voltage is now quite well understood; the behavior and recurrence can now quite well be described. Based on the knowledge of the physical background of PD processes triggered by different defects, PD plots containing information on the discharge magnitude and the time in between discharges can now successfully be used to analyze practical PD data. By studying different plots of dc PD data, often it is possible to infer the type of defect, a process which in some cases can be automated.

It was shown that, for instance in the case of HVDC mass impregnated cables, PD analysis provides information that can be used to understand the dielectric behavior of the cable.

For practical purposes, dc PD measurements can be used to distinguish between good and bad products. Depending on the type of product different criteria have been proposed.

A field that is still relatively unexplored is the field of dc partial discharges at interfaces such as may occur in cable accessories or in capacitors. Here we have the complicating factor of space charge accumulation at and near the interface. For a thorough understanding of the behavior of such interfaces, and in fact, to be able to make a proper design, there is still quite some work that needs to be done.

With the introduction of nano-materials to change the parameters of insulating materials new challenges arise. How does the interaction between these nano-materials with the host insulation affect the PD resistance?

In conclusion, we believe we could state that in the field of dc partial discharge considerable progress has been made in the last two decades. The old ASTM test requirement [51] of less than one discharge per minute can now be replaced by a variety of tests that allow us to infer much more information on the quality of the object under test.

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