Phase Resolved Partial Discharge Evaluation at dc Voltage

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Phase resolved partial discharge evaluation at dc voltage

A thesis submitted for the degree of
Doctor of Philosophy

by
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Partial discharge diagnostics are common for the condition assessment of high voltage alternating current (ac) and direct current (dc) equipment. For ac applications the phase resolved partial discharge evaluation method has prevailed [1]. Even though, numerous methods for dc partial discharge diagnostics have been proposed no agreed standard exists. This is primarily because of the fact that these methods are not as easily applicable as the well-known, intuitive, pattern based phase resolved method. Due to the often assumed unavailability of a useable phase angle information [2]–[4] this method has never been transferred to dc partial discharge diagnostics. However, as a dc voltage is usually not generated but obtained from a rectification process a natural ripple, which provides a phase information, will always be available. Hence, a novel dc partial discharge evaluation method that uses a phase resolved approach is introduced in this thesis.

The introduction of a ripple on the dc voltage, which, in this thesis, is obtained from a half-wave rectification, might alter the discharge behaviour. Consequently, the maximum tolerable ripple below which a dc discharge behaviour is maintained has to be evaluated. Such an evaluation has never been carried out for a partially rectified voltage. Hence, for the first time, four characteristic discharge quantities have been evaluated with respect to a varying ripple. The outcome is a maximum tolerable ripple of 3 % for negative corona, 2 % for positive corona, 0.8 % for negative and positive surface discharges as well as 0.4 % for internal discharges. These newly defined values have then been used as a basis to obtain characteristic phase resolved partial discharge patterns at dc voltages. The novel patterns have been explained through the underlying physical phenomena.

Therefore, for the first time, this work successfully demonstrated that a phase resolved partial discharge evaluation can be conducted at dc voltages, while the general dc discharge behaviour is maintained. This newly proposed recognition method has the potential to change dc partial discharge diagnostics in practical as well as in laboratory applications.
Declaration

I certify that this thesis which I now submit for examination for the award of Doctor of Philosophy, is entirely my own work and has not been taken from the work of others, save and to the extent that such work has been cited and acknowledged within the text of my work.

This thesis was prepared according to the regulations for graduate study by research of the Technological University Dublin and has not been submitted in whole or in part for another award in any other third level institution.

The work reported on in this thesis conforms to the principles and requirements of the TU Dublin’s guidelines for ethics in research.

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Tobias Dezenzo

Dublin, 19th September 2019
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A area.

ac alternating current.

$\alpha$ Townsend’s first ionization coefficient.

$\beta$ Townsend’s positive ion ionization coefficient.

C capacitor.

D electric displacement field strength.

d distance.

dc direct current.

E electric field strength.

$e$ elementary charge.

$\varepsilon$ permittivity of a dielectric.

$\varepsilon_0$ vacuum permittivity.

$\eta$ attachment coefficient.

$\gamma$ Townsend’s secondary ionization coefficient.

f frequency.

FFT fast-fourier-transformation.

$f_d$ discharge frequency.

H magnetic field strength.

HVAC high voltage alternating current.
List of symbols and abbreviations

**HVDC**  high voltage direct current.

$I$  current.

$\Delta \hat{i}_p$  amplitude difference of two discharge pulses.

$\bar{\hat{i}}_p$  average pulse amplitude.

$I_{TO}$  current through the test object.

$\hat{I}_{TO}$  discharge current amplitude.

$J$  current density.

$\kappa$  specific conductivity.

$L$  inductivity.

$l$  length.

$\lambda$  dimensionless scalar function.

**LCC**  line commutated converter.

$\mu$  dipole moment.

$n$  number of particles.

$\Omega$  volume.

$p$  pressure.

**PD**  partial discharge.

$\phi$  phase angle.

**PRPDA**  phase resolved partial discharge analysis.

**PRPD**  phase resolved partial discharge.

$Q$  apparent charge.

$q$  induced charge.

$R$  resistor.
List of symbols and abbreviations

$r$ radius.

$\rho$ volume charge density.

$S$ surface.

$\sigma$ surface charge density.

$t$ time.

$\tau$ time constant.

$\Delta t_p$ time between two pulses.

$\bar{t}_{ft}$ average pulse fall time.

$\bar{t}_{rt}$ average pulse rise time.

$V$ applied voltage between two electrodes.

$\Delta V_{dc}$ instantaneous value of the ac components of the dc voltage.

$V_i$ ignition voltage of a discharge.

$V_{inc}$ inception voltage.

$\bar{V}$ mean value of the voltage.

$\hat{V}$ amplitude of the voltage.

$V_{R\%}$ value of the ripple.

$V_{res}$ residual voltage.

**VSC** voltage sourced converter.

$W$ energy.
1 Introduction

"The great point in the system of M. Deprez is that he has solved the problem of the divisibility of electrical force and its transmission [...]"

The New York Times
October 22, 1882

The above quote is taken from an article about the Munich electrical exhibition in 1882, where M. Deprez had successfully erected the first long distance transmission of electrical power [5]. Deprez had transmitted 1.5 kW\(^1\) over a distance of 57 km at a voltage of about 2 kV [6]. The most remarkable aspect from today’s perspective is that Deprez had used direct current (dc). It took, however, less than ten years until another invention was made that became the standard for the transmission of electrical energy. The euphoria transported in the quote below indicates that the people of that time were well aware of the meaning of this finding for the electrical energy sector.

"I do not think that I am guilty of exaggeration in expressing an opinion that the Lauffen-Frankfort transmission is the most difficult and most momentous experiment made in technical electricity since that mysterious natural force which we call electricity has been made serviceable to mankind."

The Times
September 12, 1891

The quote is from an article about the 1891 International Electrotechnical Exhibition and reports on the first successful demonstration of a three phase alternating current (ac) transmission line [7]. Due to the advantages towards electrical machinery and the easy transform-ability ac prevailed over dc. Still, dc never became obsolete and nowadays with the invention of fast switching, high

\(^{1}\text{At the generating end.}\)
current and voltage carrying semiconductors engineers overcame the transformation problem. The frequency dependent disadvantages of alternating voltages like the skin effect, as well as capacitive and inductive losses can thus be omitted by reintroducing high voltage direct current (HVDC) transmission. Especially, the reduction in capacitive load currents of cables is one big advantage of direct current transmission over alternating current transmission. The main disadvantage of direct current transmission is the increased monetary effort that is required for the erection of the transmission lines, mainly due to the indispensable converter stations. Consequently, a breakeven point exists where the combined costs of commissioning and service conditioned losses of high voltage alternating current (HVAC) are higher than for HVDC with respect to the transmission line length. Here, [8] states 500 km for overhead transmission lines and 40 km for underground cable applications.

An illustrating example for the requirement of HVDC transmission is the change of German energy policy termed ‘Energiewende’ [9]. After the events leading to the nuclear incident in the power plant of Fukushima in Japan [10], the government of the Federal Republic of Germany has decided to accelerate the exit from nuclear energy. At that time nuclear energy contributed about 30% to the energy mix in Germany [11]. Accompanied by a strong decarbonization movement, the replacement of nuclear energy is intended to be primarily renewable [12]. As production of renewable energies is effected geographically they are not always available where they are needed. Germany for example has strong industrial areas and urbanisation in the south and the west of the country, whereas renewable energy in form of wind energy is mainly available in the north and the east [12]. In Germany this increased demand for long range energy transmission and reservations against overhead transmission lines by the population have led to a focus on cable based HVDC transmission. Two prominent examples are the two transmission lines SuedLink and Sued-Ost-Link 3. Despite the differences between HVAC and HVDC transmission the technologies share common ground in one particular aspect. That common aspect is the requirement for high voltage values. The application of high voltage leads to a series of physical processes,
which can bring the non-conductability of air and other insulating material to an end. The consequence is an outburst of energy at a sometimes undesired spot of the high voltage equipment in the form of a discharge. Even though discharges can be harmful, they usually do not directly lead to a failure of the complete insulation of high voltage equipment. They do however, constantly weaken the insulation and hence become worse over time [14]. Prolonged discharge activity may result in an outage of transmission equipment [14] and potentially lead to a blackout [15]. It is obviously one important task of high voltage engineers to prevent such discharges [1]. However, even if a device, e.g. a cable, is properly engineered discharges can become active after a long time of discharge free service due to ageing [16]. Consequently, a detection of discharges and a long-term monitoring of equipment are required to maintain and guarantee the security of supply of electrical energy.

In this section a motivation towards the detection of discharges in high voltage equipment irrespective of the voltage type has been given. In the next section the term discharge is further explained.

1.1 Partial discharges - definitions and diagnostic aspects

In the previous part of this thesis the term discharge has been introduced without further definition. The term discharge describes an electrical phenomenon that is caused by the non-ideality of insulation materials. In this context non-ideal means that the insulation can become conductive due to various physical processes, which lead to ionization.

In general discharges can be subdivided into two different categories, where each bares multiple subcategories themselves - discharges, which do bridge the electrodes and discharges which do not bridge the electrodes. Discharges, which bridge the electrodes are referred to 'complete' breakdowns, where the insulation collapse bares a low ohmic, conductive part between the electrodes [17]. Discharges, which do not bridge the electrodes ('incomplete' breakdowns [17]) are called partial discharges (PD) and according to IEC 60270:2000 are more precisely defined as [18]:

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1 Introduction

'localized electrical discharge that only partially bridges the insulation between conductors and which can or can not occur adjacent to a conductor'

The definition bares three additional notes, which shall be cited when needed.

1.1.1 Partial discharges and ageing

As indicated different types of discharges exist, which can be categorized by the media in which they occur. Most textbooks such as [4], [19], [20] differentiate between discharges in gaseous dielectrics, discharges in solid dielectrics and discharges in dielectric liquids. Of great importance for the topic of partial discharges are discharges in gaseous dielectrics as partial breakdowns in solids and liquids are mostly associated with gaseous intrusions. The complete breakdown of the insulation is however usually related to different processes [4].

Partial discharges can be distinguished by their locations. Kreuger's book [21] shows a simplified but precise graphical representation of the terminology used for partial discharges, where the three main types of discharges shall be cited here, as differentiation between discharges in this work is made based on their location of occurrence. The three main types are corona discharges, surface discharges and internal discharges.

Various effects are associated with the different types of partial discharges. They can be of enriching or damaging nature, where enriching is meant by means of commercial use. Corona can be used for [22], [23] chemical synthesis e.g. ozone, or as an ion source for electrostatic precipitators and printers. Combustion gas treatment and surface treatment e.g. adhesivity of polymers, are additional examples for the useful character of corona. The damaging effects include [21], [24] heating of discharge channels as well as electrode materials due to electron and ion bombardment or surface erosion due to ion bombardment. A discharge can lead to chemical by-products and chemical processes in the gas and at the surfaces such as ozone, acids and polymerization. Radiation and power losses are to be observed as well.

The mechanical and chemical processes are of utmost concern as they might lead to insulation degradation and finally enforce a breakdown of the dielectric. This holds especially true for non-self-healing insulation media such as solids
and liquids. The question which consequently arises is whether or not partial discharges lead to a breakdown of the insulation and if so is there a difference between the mechanisms involved at ac and dc.

For alternating voltages a coherence between partial discharges, insulation deterioration and breakdowns has long been known, as can be seen by the comprehensive treatment of the topic in a book by Whitehead [25] published in the early fifty’s. A first description of the processes leading to breakdown for internal discharges was given by Mason [26], who used four consecutive steps. According to Mason internal PD lead to erosion of the surface of the dielectric being followed by a strong concentration of the discharges at the surface of the void. These discharges lead to the formation of pits and finally a complete breakdown due to the growth of the pits and the resulting conducting paths. Temmen [27] introduced another model for PD induced ageing. Temmen stated that at first PD activity in a void inside of a dielectric is determined by the space charge of preceding discharges. This stage is followed by an increase in surface conductivity due to humidity and other PD generated separation products of air. The next step is characterized by ion bombardment of the cavity surface as well as chemically induced erosion. Both activities contribute to an increased surface roughness, which leads to tip formation and therefore, local field enhancement. As a result the formation of crystals is to be observed at the cavity surface, which is correlated with further chemical deterioration of the insulation. Treeing is to be observed in the vicinity of the crystals due to the resulting field enhancement, which finally leads to a breakdown of the insulation.

In 1995 Kreuger wrote a first book that was solely devoted to dc fields, breakdown and related tests [28]. In this book it is stated that the influence of PD under dc on the breakdown behaviour is unclear. Hence, in the early years of dc partial discharge tests, the strongly harmful influence of PD under ac voltage could not be proven for dc. For example, Rogers and Skipper calculated that the life time of a dc polythene cable that is subjected to PD will be in the range of $10^7$ hours [29]. They argued that this is caused by the low repetition rates of the discharges, especially in voids in solid dielectrics. To increase the discharge rate a ramp-technique was introduced, where the voltage is raised in steps using a predefined rate of dV/dt [30]. The discharge activity is measured during the rise of the voltage and within included plateau-times [30]. This technique did also
not lead to a direct correlation between discharges and breakdown at dc voltage [30]. However, there was no doubt that PD, even at dc, indicated weak spots [28] in the insulation and is therefore, worth to be identified. A strong indication for an underlying ageing process leading to breakdown at dc voltage was shown for artificial epoxy-resin samples by Fromm [31]. He showed that a long term application of dc voltage leads to an increase in failure probability over time in the presence of a void compared to samples without a void. Smit showed that surface discharges under dc have carbonising effects on capacitors, which also indicate an ageing process [32]. Even though, improved manufacturing processes drastically reduced the size of voids inside of dielectrics [33] a relationship between ageing and the presence of voids with the size of micrometers in HVDC cables was modelled and fitted to experimental data [34], [35]. The authors of [36] have indicated that the partial discharge inception voltage is lowered equally after minutes of partial discharge application as compared to thousands of hours of thermal ageing. Recently, Li et al. [37] have shown that the breakdown voltage of oil immersed pressboard decreases after prestressing the samples with dc PD activity above 1 nC. They also illustrated a change of the surface roughness of the pressboard samples. These considerations indicate that partial discharges can be a serious component in the processes leading to ageing of an insulation material. Furthermore, as partial discharges indicate weak spots in the insulation media their measurement and interpretation is a useful, if not the most useful, tool in insulation diagnostics for high voltage equipment.

1.1.2 Dc fields, ac fields and their differences

In the previous section it was shown that partial discharges can lead to damage or destruction of high voltage components. The detection, interpretation and analysis of partial discharges is therefore a necessary tool in the area of high voltage engineering. For these purposes numerous techniques have been developed in the last decades to acquire and work with partial discharge data. All of which, have mainly in common that they are based on diagnostics for alternating fields due to the relevance of alternating voltage for energy transportation. One major aspect in this context is the testability of dc components with alternating voltage. This important aspect shall be accessed in this subsection.

The following considerations are based on quasi stationary fields, which can be
applied if the change of fields will take place nearly simultaneously at all locations considered [4]. The application of a dc voltage to a composite dielectric, as shown in Figure 1.1, leads to a resistive distribution of the applied voltage\(^4\).

![Figure 1.1: A dielectric consisting of two layers with different permittivities, \(\varepsilon_a, \varepsilon_b\), conductivities, \(\kappa_a, \kappa_b\), and thicknesses, \(d_a, d_b\). Adapted from [38].](image)

This can be shown by using amperes law.

\[
\oint_C \vec{H} \, d\vec{s} = I = \int_A \left( \vec{J} + \frac{\partial \vec{D}}{\partial t} \right) \, d\vec{A}
\]  

(1.1)

with

- \(\vec{H}\) magnetic field strength
- \(\vec{J}\) current density
- \(I\) current
- \(\vec{D}\) displacement field strength
- \(d\vec{s}\) infinitesimal element of length
- \(d\vec{A}\) infinitesimal area element

As the displacement field will not change with respect to time its derivative in (1.1) yields 0. Therefore, no displacement current will be present and the current is solely a conduction current. The directions of the current density vector, \(\vec{J}\), and the area vector, \(\vec{A}\), are perpendicular, (1.1) can thus be rewritten as:

\[
I = JA
\]

(1.2)

\(^4\)cf [38]
Applying continuity law and the material equation leads to:

$$I = \kappa EA = \kappa_a E_a A = \kappa_b E_b A$$  \hspace{1cm} (1.3)

with

- $E$, electric field strength
- $E_a$, electric field strength across the dielectric $a$
- $E_b$, electric field strength across the dielectric $b$
- $\kappa$, specific conductivity of the material
- $\kappa_a$, specific conductivity of the dielectric $a$
- $\kappa_b$, specific conductivity of the dielectric $b$

The voltage across the dielectric, $V_{ab}$, is then equal to [38]:

$$V_{ab} = \int_a^b \vec{E} \, \mathrm{d}s = E_a d_a + E_b d_b$$  \hspace{1cm} (1.4)

where $d_a$ and $d_b$ are the thicknesses of the dielectrics. The quotient of (1.4) and (1.3) reveals Ohms law, which proofs the resistive character of the voltage distribution.

$$\frac{V_{ab}}{I} = \frac{E_a d_a + E_b d_b}{\kappa EA} = \frac{d_a}{\kappa_a A} + \frac{d_b}{\kappa_b A} = R_a + R_b$$  \hspace{1cm} (1.5)

with

- $R_a$, resistance of the dielectric $a$
- $R_b$, resistance of the dielectric $b$

The current in Equation (1.5) can be substituted by the desired voltage component e.g. the voltage across dielectric $b$, $V_b$, and the corresponding resistor:

$$V_b = V_{ab} \frac{R_b}{R_a + R_b}$$  \hspace{1cm} (1.6)

Following a similar approach the capacitive behaviour of an ac field across a composite dielectric can be shown. It is important to note that in this case the displacement field does change with respect to time and that usually $\varepsilon_0 \varepsilon_r \frac{\partial E}{\partial t} \gg \kappa E$ [4]. This leads to a dominant displacement current, where the conduction
current can be neglected. Therefore, (1.1) can be rewritten as (effective values assumed):

\[
I = \int_A \left( \frac{\partial \vec{D}}{\partial t} \right) d\vec{A} = \frac{\partial D}{\partial t} \cdot A = \frac{\partial \varepsilon_0 \varepsilon_a E_a}{\partial t} \cdot A = \frac{\partial \varepsilon_0 \varepsilon_b E_b}{\partial t} \cdot A \quad (1.7)
\]

with

- \( \varepsilon_0 \): vacuum permittivity
- \( \varepsilon_a, \varepsilon_b \): relative permittivity of the dielectric a and b

The corresponding charge, \( Q \), can be calculated by introducing a time integral.

\[
\int I dt = Q = \int \frac{\partial \varepsilon_0 \varepsilon_a E_a}{\partial t} \cdot A dt = \varepsilon_0 \varepsilon_a E_a A = \varepsilon_0 \varepsilon_b E_b A \quad (1.8)
\]

where

- \( C_a \): capacitance of the dielectric a
- \( C_b \): capacitance of the dielectric b

If the voltage is calculated according to (1.4) then the capacitance, \( C \), which corresponds to the voltage and the deposited charge can be derived:

\[
C = \frac{Q}{V_{ab}} = \frac{\varepsilon_0 \varepsilon_a E_a A}{E_a d_a + E_b d_b} = \frac{\varepsilon_0 \varepsilon_a A}{d_a + \frac{\varepsilon_a A}{\varepsilon_b d_b}} = \frac{C_a C_b}{C_a + C_b} \quad (1.9)
\]

The voltage drop per dielectric can then be expressed as:

\[
V_b = V_{ab} \frac{C_a}{C_a + C_b} \quad (1.10)
\]

Finally, if a combined ac and dc field is present e.g. if a dc voltage is switched on or an ac voltage is superimposed on a dc voltage or vice versa, then the total current is composed of a conduction and a displacement component. The current flowing through the composite dielectric is then given by:

\[
I(t) = \kappa_a E_a(t) A + \frac{\partial \varepsilon_0 \varepsilon_a E_a(t)}{\partial t} \cdot A = \kappa_b E_b(t) A + \frac{\partial \varepsilon_0 \varepsilon_b E_b(t)}{\partial t} \cdot A \quad (1.11)
\]
1 Introduction

The potential difference between the dielectric is then time dependent

$$V_{ab}(t) = E_a(t) \, d_a + E_b(t) \, d_b$$  \hspace{1cm} (1.12)

and hence the electric field across one of the dielectrics becomes

$$E_a(t) = \frac{V_{ab}(t) - E_b(t) \, d_b}{d_a}.$$  \hspace{1cm} (1.13)

Substituting (1.13) into (1.11) leads to the following first order differential equation for the electric field $E_b(t)$:

$$\frac{\varepsilon_a \partial V_{ab}(t)}{\varepsilon_0 \varepsilon_a d_b + \varepsilon_0 \varepsilon_b d_a} \partial t + \frac{\kappa_a V_{ab}(t)}{\varepsilon_0 \varepsilon_a d_b + \varepsilon_0 \varepsilon_b d_a} = \frac{\partial E_b(t)}{\partial t} + E_b(t) \frac{\kappa_a d_b + \kappa_b d_a}{\varepsilon_0 \varepsilon_a d_b + \varepsilon_0 \varepsilon_b d_a}$$  \hspace{1cm} (1.14)

The homogeneous solution can be found by using an exponential approach. The resulting, relaxation time constant, $\tau$, is given by:

$$\tau = \frac{\varepsilon_0 \varepsilon_a d_b + \varepsilon_0 \varepsilon_b d_a}{\kappa_a d_b + \kappa_b d_a} = \frac{R_a \cdot R_b \cdot (C_a + C_b)}{R_a + R_b}$$  \hspace{1cm} (1.15)

The forgoing considerations strongly emphasize that alternating fields, direct fields and combined fields lead to a different behaviour of the dielectric, which is subjected to those fields. One direct relation that can be derived is the varying voltage distribution and the associated electric field behaviour. If, for example, a void inside of a solid dielectric is considered then it is possible that the void breaks down due to an alternating voltage stress but withstands a direct voltage application. The requirement to perform dc voltage driven tests for dc devices and ac voltage tests for ac devices is a clear consequence.

1.2 Aim of this thesis

The previous subsections indicated the requirement for the detection of partial discharges as they can lead to breakdown of the insulation of high voltage devices or indicate at least weak spots in the insulation. It has been furthermore argued that partial discharge tests for HVDC equipment have to be carried out using dc voltage due to the different field behaviour of ac, dc and combined voltages. The requirement for the use of dc voltage introduces the main challenge for partial
discharge diagnostics. This challenge is caused by the inapplicability of the well-known ac phase resolved partial discharge (PRPD) diagnostic method for dc PD purposes. The general idea behind this method is to relate the measured partial discharges to their phase of occurrence with respect to the applied ac voltage. The advantage of this method is that every defect produces a, more or less, unique pattern that can be used to distinguish between different types of defects. As dc usually contains no phase information this method is not applicable. Hence, numerous other techniques have been developed and evaluated towards their ability to distinguish the different forms of partial discharges from one another e.g. [31], [39], [40]. However, none of these methods is able to easily distinguish the different types of defects. Even more important, most of them require intense post processing of the measured data, which makes a real time evaluation of the measurements difficult, if not impossible. The requirement for a PD diagnostic method that is as powerful as the ac PRPD method, for dc voltage is therefore given. It has consequently been decided to base the novel, in this thesis proposed method on the ac PRPD approach. The main advantage of this is that the knowledge gained with PRPD at ac, in the last decades, can be utilized. To enable the use of PRPD for dc PD purposes the ripple that is naturally present on dc voltages is used to obtain a phase relation. To prove the usability of PRPD for dc the three previously introduced main types of partial discharges, namely corona, internal discharges and surfaces discharges are evaluated towards their characteristic patterns at positive and negative voltage. The dc voltage used is obtained by half wave rectification of an ac voltage. Due to the introduction of a ripple on the dc voltage the signal is composed of a dc component, and multiple ac components. The resulting electric field is hence not a pure dc field and the discharge behaviour might be altered. However, as has been shown in Subsection 1.1.2, a turning point exists below which a combined field can be treated as a dc field. Hence, it is necessary to experimentally validate the applicability of the proposed method in terms of a maximum tolerable and a minimum required ripple. The maximum tolerable ripple ensures that the discharge behaviour is still a dc behaviour. The minimum required ripple is needed for the distinguish-ability of the patterns.

Therefore, the main goal of the thesis is to introduce a novel partial discharge representation method for dc PD. This method is based on the ac PRPD approach and uses the ripple that is naturally present on dc voltages to obtain a phase relation. The method is experimentally validated in terms of a maximum tolerable and a minimum required ripple. A more complete review on the different existing dc PD representations is given in Section 3.1.
diagnostic technique, that is based on the ac PRPD method, for dc purposes, while maintaining the dc discharge behaviour. To achieve this goal the following steps are necessary:

- Identify the maximum tolerable ripple to maintain a dc like discharge behaviour.
- Physically explain the ripples influence on characteristic discharge parameters.
- Estimate the minimum ripple to produce clearly recognizable patterns.
- Investigate the different observable patterns and related them to their physical cause of formation.

1.3 Thesis outline

The remainder of the thesis is outlined as follows. Chapter 2 presents the required theoretical background to understand the physical processes which are related to this work. The main types of gas discharge mechanisms are presented in Section 2.1. The three types of partial discharges, corona, internal PD and surface PD, which are evaluated in this thesis are outlined in Sections 2.2, 2.3 and 2.4, respectively. The proposed test method, the evaluation method and a description of the measuring circuit as well as the used test samples are given in Chapter 3. In Chapter 4, Chapter 5 and Chapter 6 the measurement results with respect to the different observable patterns, the influence of the ripple on the discharge behaviour as well as the underlying physical phenomena are given. The conclusions taken from this work are drawn in Chapter 7 and possible further research is proposed in Section 7.3.
2 Partial discharges - sources and mechanisms

In this chapter the theoretical background of partial discharges as needed in this thesis is described. The three main gas discharge mechanisms, the Townsend, the streamer and the leader mechanism are presented in Section 2.1. In Sections 2.2 to 2.4 the partial discharge subtypes corona, internal partial discharges and surface partial discharges are explained based on the underlying physical phenomena.

2.1 Gas discharge mechanisms

Mainly three mechanisms exist which lead to the breakdown of gaseous insulating materials. These are the Townsend mechanism, the streamer mechanism and the leader mechanism. The different processes leading to breakdown according to the Townsend mechanism are given in Subsection 2.1.1. Streamer breakdown is explained in Subsection 2.1.2 and the leader mechanism is presented in Subsection 2.1.3

2.1.1 Townsend mechanism

John Sealy Edward Townsend was the first to give a description of electron multiplication by collision and secondary emission. The physical process is named after him - the Townsend mechanism. His concepts are summarized in his first book\(^6\) [42]. Townsend postulated that if two parallel plates are subjected to a large electrical force, then the measurable current is caused by the generation of new ions by collision. He stated that at first negative ions (electrons) are the relevant particles and only at higher stresses positive ions contribute as well. To proof his hypothesis he argued that at a constant force, the measurable current,

\(^6\)Care has to be taken as Townsend first used the term negative ions instead of electrons [41]. Therefore, whenever a misleading term is used today’s nomenclature is added in parenthesis.
will vary with the plate distance as the number of newly produced ions by collision will also increase with the distance. This could be experimentally proven. He gave a mathematical expression that describes the number of ions arriving at the opposite plate. Nowadays it is used to calculate the number of electrons, $n$, including produced electrons, after the initial electrons, $n_0$, traversed a distance, $d$, through a gap if impact ionization is the only electron multiplication process [43]. It is given by [43]:

$$n = n_0 \cdot e^{(\alpha d)}$$  \hspace{1cm} (2.1)

The primary ionization coefficient\footnote{or Townsend’s primary ionization coefficient [43].}, $\alpha$, is defined as "[...] the number of new electrons created per centimeter path in the field direction." [44, p.23]. The parameter $\alpha$ depends on the type of gas, its pressure, $p$, and the electric field strength, $E$. It is usually represented in graphs that are of the form:

$$\frac{\alpha}{p} = f \left( \frac{E}{p} \right)$$  \hspace{1cm} (2.2)

By comparing experimental data with calculated values of $\alpha$, Townsend had realized that for large values of $E/p$ and increased plate distances, $d$, a divergence between calculated and experimentally estimated primary ionization coefficient exists. He concluded that "[...] some other form of ionization has come into play." [42, p.38]. Townsend then introduced an equation that also involves electron generation by impact ionization of molecules by positive ions. However, the corresponding ionisation coefficient, $\beta$, is much smaller then $\alpha$ and can mostly be neglected [38]. In his second book from 1915 Townsend derives an equation, which introduces the generation of electrons by secondary emission due to collision of positive ions with the cathode [45].

$$n = n_0 \frac{e^{\alpha d}}{1 - \gamma (e^{\alpha d} - 1)}$$  \hspace{1cm} (2.3)

with

$\gamma$. Townsend’s secondary ionization coefficient

This equation is still used nowadays, but with some minor modifications. Firstly,
either an attachment coefficient, $\eta$, which represents the disappearance of electrons due to attachment, is subtracted from the primary ionization coefficient [43] or the coefficient is changed into an effective ionization coefficient, $\alpha_{\text{eff}}$, which includes attachment [38]. Secondly, it has to be noted that the secondary emission coefficient is not only related to electron emission by ion bombardment of the cathode, $\gamma_i$, but also to various other effects such as electron emission by photon impact, $\gamma_p$, and diffusion of metastable atoms, $\gamma_m$, [38], [44].

Up to this point primary and secondary electron generation have been treated as to contribute to one single electron avalanche. However, it is obvious that the secondary electrons, which start from the cathode, as did the primary starting electron that caused the original avalanche, can initiate another avalanche. Therefore, a series of avalanches will be maintained as long as every starting electron produces at least one other electron. The succession of avalanches will result in the formation of a conducting channel - a breakdown of the insulation [38]. From (2.3) the corresponding Townsend breakdown criterion can be derived [38]:

$$\gamma \left( e^{\alpha d} - 1 \right) \geq 1 \quad (2.4)$$

Up till now only homogeneous field arrangements, which show a constant field behaviour, have been discussed. In non-uniform fields the electrical field strength varies across the electrode interspacing. A variation of the electrical field also leads to a variation of the ionization coefficient, $\alpha$. Consequently, the ionization coefficient becomes a function of position and the breakdown criterion takes an integral form. The Townsend breakdown criterion is then given by [19]:

$$\gamma \left( e^{\int_0^d \alpha_{\text{eff}} \, dx} - 1 \right) = 1 \quad (2.5)$$

From the above equation it can be seen that the breakdown criterion does not necessarily have to be fulfilled for the entire length of a gap under consideration. Moreover, it can be fulfilled for a limited area of the gap. This area is strongly correlated towards the grade of inhomogeneity of the electric field. Due to the range limitation of the resulting breakdown, the breakdown is referred to a partial breakdown or partial discharge.
2 Partial discharges - sources and mechanisms

2.1.2 Streamer mechanism

It is important to note that the Townsend mechanism is limited to values of $\alpha d < 20$ and space charge free fields [38], [46], [47]. Breakdown also exists above the specified value and in fields, which are mainly characterised by space charges. To account for the breakdown formation in gases that are subjected to high field stresses Raether and Meek and Loeb have independently developed the theory of the streamer mechanism. The findings and explanations of the authors are best summarized in [47]–[50] and shall be partially reproduced here with the aid of [19] to present a general understanding of the underlying physical occurrences in contrast to the Townsend mechanism.

If an electron avalanche is initiated by a photoelectron from the cathode under field conditions of $\alpha d > 20$ then the electrons will rapidly advance towards the anode, whereas the positive ions can be treated as being static due to their comparably slow movement. This results in a spherical concentration of electrons, which broadens on its way towards the anode because of diffusion and a conical shaped concentration of positive ions. The first part is called head and the second part is called tail. Due to the large amount of electrons in the head (about $10^8$) and associated positive ions in the tail an unneglectable space charge is created. The space charges enhance the field between the anode and the head and the tail and the cathode, whereas the field between head and tail is reduced. In combination with the external field photons are emitted in front of the head, which can lead to secondary electrons by photoionization. These can in turn result into secondary avalanches. Due to the high speed of the photons rapid development of a streamer (conducting channel) is possible.

2.1.3 Leader mechanism

So far gas discharge mechanisms, which occur in uniform and non-uniform fields have been presented. They were driven by collisional ionization and photoionization. In longer gaps at high field stresses or across dielectric surfaces another discharge mechanism can be active. It is driven by an additional form of ionization, the thermal ionization, which is caused by gas heating due to large current flow. This discharge type is called leader discharge [38]. A comprehensive review of the topic is given in [51]. The leader discharge itself consists of two main
2 Partial discharges - sources and mechanisms

parts. These are, the leader channel [52], and the head or stem [53], also referred to as tip. Furthermore, the authors of [54], subdivide the head into the channels head and the streamer zone, which shall be adopted here. The generally agreed precursor of such a leader discharge is an initial series of streamers [38], [52], [53]. The leader builds up from the stem of these streamer discharges if the gas has been sufficiently heated due to the Joule effect [52]. The channel of the leader becomes highly conductive i.e. it transfers the electrodes potential to the head of the leader [51]. The formation of a new section of the leader discharge is caused by streamers that originated from the head of the leader [54]. The current of these streamers is fed into one thin channel where again the gas is heated and thermal ionization takes place [55]. The electric field at the tip of the leader channel and at the current collecting streamers influences the leaders propagation. The electric field varies with the voltage drop across the leader channel and the charge induced in the streamer head and the cover. In the first case the voltage drop increases with increasing channel length. Consequently, the charge and potential in the streamer head are reduced and so is the electric field. In the second case space charges in the gap induce a charge, which is of opposite polarity of that of the leaders head charge. The result is a reduction of the electric field in the leader tip [54]. The elongation of the leader results in a reduced field at the tip at a constant voltage, which hinders the leaders advancement [54]. As the leader advances through the gap it pierces through space charges, which have been generated by streamers at the leaders head. These space charges then accumulate around the leaders channel in form of a cover, which reduces the radial expansion of the leader channel [54]. There is a general difference between positive and negative leader discharges [51], which shall not be further incorporated here as leader discharges in air are unlikely to occur in the experiments conducted in this thesis due to the short electrode interspacing.

2.2 Corona Discharges

The term corona is defined in note 2 of the definition of partial discharges in IEC 60270:2000 [18].

"Corona" is a form of partial discharge that occurs in gaseous media around conductors which are remote from solid or liquid insulation.
Corona should not be used as a general term for all forms of PD."

For a more detailed explanation of the processes leading to a corona discharge differentiation based on the polarity (negative and positive) of the voltage that drives the discharge has to be made. This differentiation is required as the polarity of the voltage influences the potential gradient and the behaviour of the electrons as well as ions [56]. All explanations are given on the basis of a point to plane arrangement as shown in Figure 2.1, which is one of the typical artificial defects for research in the area of corona discharges. Additionally, the processes presented are related to electron attaching (electronegative) gases such as O₂ only, as otherwise also a differentiation based on the gas or gas mixtures due to the different space charge behaviour has to be made [44].

![Figure 2.1: Point to plane configuration.](image)

### 2.2.1 Negative corona

In 1938 Trichel [57] was the first to conduct a systematic study on negative corona and the related space charge phenomenon. According to him a negative corona discharge can be explained as follows:

The electric field strength in the vicinity of the point e.g. Figure 2.1 has to be high enough to give a sufficient amount of energy to a positive ion that the ion produces at minimum one secondary electron by ion bombardment. The secondary emission coefficient of Townsend, γ, is related to the liberation of such a secondary electron. This secondary electron travels into a region where the field is dense enough so that the electron can produce more free electrons by inelastic collision with molecules, itself. The same holds true for the newly produced
electrons as well as for all following generations of electrons. Consequently, the number of electrons increases exponentially. If the electrons move to weaker field regions the number of generated ions decreases and so does the number of electrons. The electrons can then combine with O2 molecules causing negative ions, which form a negative space charge. The positive ions, which slowly move to the point form a positive space charge. The positive ion cloud causes an increased field near the tip, facilitating the electron emission by ionization and secondary emission. In contrast to this, the field behind the space charge is decreased, which results in reduced ionization. As the positive space charge approaches the tip the impact ionization stops. After the majority of positive ions have disappeared over the cathode the process can start again. Due to the conducted research these regularly reoccurring pulses are called Trichel pulses.

At the time Trichel did not consider effects that happen outside of the Trichel regime e.g. glow discharges or negative streamers. Unfortunately, also the model presented did not hold true as it was found that not the positive ions but rather the negative ions are responsible for the discharge interruption [58]. They form into a space charge, which lowers the field in the ionization region below the critical value and have to move sufficiently far away before a new discharge can ignite. The research of Lama and Gallo [59], supported this postulation, as they argued that many negative ion clouds will simultaneously traverse through the gap. Furthermore, the negative ion clouds only have to travel sufficiently away from the tip so that the electric field can build up again to start a new discharge. The introduction of numerical simulations leads to more insight into the formation of Trichel pulse corona. A one-dimensional model based on the simultaneous solving of the continuity equations for electrons, positive ions, negative ions and the Poisson equation, has been used by Morrow [60]. This model was able to provide accurate results for a single pulse. However, subsequent pulses could not be simulated. One of the most recent models [61] is a two dimensional one (radial and axial), which uses a finite element based approach to simulate the electrical field behaviour. Based on this model a maximum electron density at approximately half pulse rising was estimated. The positive ion density reaches its maximum at the peak of the pulse. Even though not explicitly stated it is the authors opinion that their results indicate that the electron avalanches are choked off by the developing positive ion cloud. This postulation is supported by
a paper of Dordizadeh et al. [62]. In this paper the authors showed a reduction of the pulse rise time with increased positive ion mobility, while all other parameters were kept constant. One possible explanation for this behaviour could be the faster positioning of the positive ions at a distance from the cathode were the ionization region is too narrow to sustain impact ionization. The foregoing considerations led the author to the following description of the processes involved in a single Trichel pulse. The description is graphically illustrated in Figure 2.2. A corresponding current pulse is given in Figure 2.3. The different time instances are represented in () in the text.

![Figure 2.2: Physical processes during the ignition of a Trichel pulse. Electrons, atoms, positive ions and negative ions are represented by a blue dot, an unfilled circle, a filled circle (red) and a circle with a blue dot, respectively.](image)

At first a starting electron in an electric field, sufficiently high to cause ionisation by impact has to be available. This electron can then produce new electrons
by impact ionisation on its way to the anode. Those newly produced electrons in their turn can also produce electrons by impact ionisation. A by-product of the ionisation process are positive ions (1), (2). Due to the higher mobility of electrons they move away very rapidly and the positive ions slowly advance towards the cathode. While, the positive ions approach the cathode the field in the vicinity of the anode is enhanced and decreased in the remainder part of the gap. Thus, an ionisation region and an attachment region are formed. In the ionisation region impact ionisation is increased, whereas in the attachment region electrons can combine with atoms to form negative ions. If positive ions with sufficient energy hit the cathode, secondary electrons can be liberated from the cathode (3). The continuous movement of the positive ions towards the cathode leads to a continuous shrinking of the ionisation region up to a point where impact ionisation mostly ceases. At this point the discharge current has reached its maximum. Attachment of secondary electrons is then the dominant process (3.1). During the decay phase of the pulse secondary emission due to cathode bombardment is still active, therefore the current does not directly decay towards zero. A complete suppression of ionisation is reached when the negative ions form into a space charge very close to the cathode (3.2). A new discharge can commence when the negative ions have travelled sufficiently far away and the electric field is restored to a value high enough to cause ionisation (4).

![Figure 2.3: A Trichel pulse with indicated development stages.](image)

If the electrical field strength is not high enough to lead to ionization of the gas and hence, the formerly described process is not active, then a current is still
measurable, which is caused by electron and ion drift [56] from natural radiation such as cosmic rays or radioactive materials [63]. This current is called background current. It is in the range of $10^{-14}$ A [56] and has first been mentioned by Bandel [64]. Bandel also showed that an increase of the voltage above the Trichel regime changes the appearance of the negative corona discharges from the regularly recurrent Trichel pulses to a constant current glow. Giao and Jordan [65] explained the transition with a change in negative space charge behaviour. Its evasion into the anode direction is enhanced as well as its formation rate is reduced. Hence, ceasing of the corona discharge will be prevented. They support their explanation by showing that the pulseless glow discharge develops out of the plateau of a Trichel pulse. At even higher voltage the glow discharge can transform into negative streamers, which usually result into a spark for short gap sizes [66].

To conclude this subsection the series of events from negative corona onset to breakdown with respect to an increasing field strength shall be recapitulated. At first a small background current can be observed. The second stage is characterized by Trichel pulse activity. At even higher field strengths the Trichel pulses transform into a pulseless glow discharge. Afterwards the glow discharges develop into negative streamers and subsequently into an arc.

2.2.2 Positive corona

The application of a positive voltage to a point to plane arrangement in air leads, as in the negative voltage case, to several different forms of gas discharges depending upon the electric field stress. If the field is too weak to cause ionization, a small background current that is caused by natural radiation is the first phenomenon to be observed [67]. A further increase of the voltage leads to burst pulses, which have again first been studied by Trichel [68]. These pulses are characterized by strong fluctuations in the current amplitude, which gives rise to the assumption that a burst is composed of multiple succeeding electron avalanches. Soon after the revelation of burst pulses, Kip [69] observed that actually two types of discharges are present near the corona onset. One of which are Trichels burst pulses and the others are streamers\(^8\). He also found that streamers could

\(^8\)These streamers are sometimes referred to as 'onset streamers' to distinguish them from 'breakdown streamers' [56], [63], [66], which occur just before spark.
be directly followed by burst pulses. In a consecutive study Amin [70] revealed that the long duration\(^9\) of the burst pulses and their rippled appearance on the falling flank was actually caused by an RC-time constant and the poor resolution of the, at this time, available oscilloscopes. Amin also postulated that a burst pulse is an initial streamer followed by consecutive (secondary) streamers. Loeb concluded from Trichels and Kips experiments that a negative ion space charge in the vicinity of the anode is required to give rise to burst pulses but later proposed the theory that positive ions of a streamer reduce the field strength in the vicinity of the anode choking of the streamer, giving rise to burst pulse activity [44]. Burst pulses will in general spread across the electrode [66], whereas streamers develop into the gap. Marrow and Blackburn [71] showed in a simulation\(^10\) that the electric field in the vicinity of the anode will rise again after the positive ions, which have been created during streamer propagation, in the streamer channel have moved sufficiently far away. This high field strength in combination with a starting electron will start a new streamer that can propagate in the original plasma channel. They estimated the level of the secondary pulses to be about 10 percent of the original pulse and stated that almost no negative ions are present in the vicinity of the anode. Their use of the term burst pulses for the primary-secondary streamer mechanism is somewhat misleading.

In the following the foregoing considerations shall be brought into a complete picture of the processes involved in streamer and burst pulses. The graphical illustrations shown in Figure 2.4 have been created with the aid of [44]. The initiations of a burst pulse or a streamer is again triggered by a starting electron in an electric field sufficiently high to cause impact ionisation. The result is a liberated electron and a positive ion (2). The original electron and the liberated electron can liberate additional electrons and create further positive ions and so on. The consequence is the formation of an electron avalanche that approaches the anode. Due to the much faster electron propagation the avalanche resembles the form of an ice cream cone (3). Its head mostly contains the electrons and the tail the slower moving positive ions thus enhancing the field between avalanche head and anode. Ionisation is therefore increased in the vicinity of the anode. When the avalanche approaches the anode the electrons can vanish

\(^9\)Kip in his 1939 paper [69] mentions burst pulses in the millisecond range.  
\(^10\)The simulation is mainly a continuation of a previous streamer simulation of Morrow and Lowke [72].
and the positive ions are left behind in front of the anode. The positive space charge in front of the anode enhances the field in the reminder of the gap and electrons are liberated by photoionisation (4.1). Due to this process a channel, which mainly contains positive ions and electrons grows towards cathode. The photoionisation is primarily active in front of the growing streamer (5). It is also possible that leftover positive space charges from a previous streamer (or burst) hinder the advancement of a streamer towards the cathode and a radial spread of the photoionisation in a lower field region is observed. If the newly developing streamer is choked off by a positive space charge it is called burst pulse (4.2).

![Figure 2.4: Physical processes during the ignition of a streamer and a burst pulse. Electrons, atoms, positive ions are represented by a blue dot, an un-filled circle and a filled circle (red), respectively.](image)

If the voltage is further increased glow corona, comparable to the negative glow, can occur. This glow type is sometimes referred to as Hermstein’s Glow
[44], [66], who gave a first physical explanation for the transition of positive streamers into the anode glow. In his paper [73] from 1960 he pointed out that during streamer discharge activity an enormous amount of negative ions will be created by absorption of electrons by oxygen molecules. This effect will occur if electrons are liberated due to photo-ionisation in weak field regions. These negative ions will wander slowly towards the anode where they form a negative space charge. This space charge will strongly enhance the field near the anode. Due to the short distance between anode and negative space charge the free path of electrons will on the contrary be reduced so that streamers cannot start. The consequence is that discharges are not able to propagate through the negative space charge but can spread laterally. This forms the glow discharge, which shows a constant current characteristic. Despite Hermstein's assumption of a pulseless glow corona, Mukutmoni [74] reported a pulsation of the positive glow corona at about 300 kHz. However, it took until the late 1970's until authors, such as [75] re-reported a fluctuating behaviour of the glow corona. Morrow [76] later obtained the following explanation for the 'pulsed positive glow corona' discharge mechanism: Positive ions generated by a discharge reduce the electric field and choke off the discharge. The positive ions are attracted by the cathode and will wander into the gap. If they have moved sufficiently far away another pulse can be triggered if a starting electron due to detachment from a negative ion is available. The process then repeats itself, resulting in many separated positive ion clouds moving towards the cathode. The discharge current is then composed of a dc component and reoccurring pulses. The number of positive ions will always be much greater than electrons and negative ions near the anode, as they are swept away due to the anode potential. At a further increased anode potential pre-breakdown streamers can develop, which are superimposed [66], [77] on the Hermstein glow.

To conclude this subsection the series of events from positive corona onset to breakdown can be summarized with respect to increasing field strength. As is the case with negative corona at first a background current is present. Afterwards, burst pulses develop, which can be accompanied by onset streamers. At increased field strength positive streamers ignite, which are followed by burst pulses. The burst pulses can at even higher field strengths develop into the pulsating glow discharge. Pre-breakdown streamers mark the final stage before an arc occurs.
2.3 Internal partial discharge

The term internal partial discharge is used for discharges that take place due to inclusions in solid or liquid dielectrics. Kreuger [21] points out that the inclusions are usually characterized by low dielectric strength as compared to the surrounding dielectric. Therefore, the breakdown voltage of the inclusion is lower when compared to the surrounding solid dielectric. One typical type of inclusion is a gas filled cavity, which can either be dielectric or electrode bound. An example of a dielectric bound cavity is depicted in Figure 2.7. Due to the theory presented in Subsection 1.1.2 it is appropriate to adapt a capacitive equivalent circuit to model the discharge behaviour of internal partial discharges when an ac voltage is applied to the test sample. This has first been done by Gemant and Philipoff [78]. The abc-equivalent circuit or sometimes referred to as three-capacitance model is exemplary depicted in Figure 2.5 b). The three capacitors $C_a$, $C_b$ and $C_c$ represent the rest of the dielectric, the dielectric in series with the cavity and the cavity, respectively [21].

![Diagram of internal partial discharge](image)

Figure 2.5: Solid dielectric with a gaseous intrusion a) and corresponding capacitive equivalent circuit b). Adapted from [21], [79].

It is now considered that at the inception voltage, $V_i$, a discharge takes place inside of the cavity. The charge of the discharge pulse, $\Delta Q_c$, can be expressed as
\[ \Delta Q_c = C_c \cdot \Delta V_c \] (2.6)

where \( \Delta V_c \) is the voltage drop at the cavity, which is in a first approximation assumed to be identical to the difference between zero and the ignition voltage, \( V_i \), of the discharge. This is in the foregoing consideration the inception voltage, \( V_{inc} \). The charge \( \Delta Q_c \) cannot be measured directly at the void as no terminals are available. The only accessible terminals are the electrodes of the test object. The external measurable voltage drop, \( \Delta V_a \), will be much smaller due to the voltage division between \( C_a \) and \( C_b \) [21], [38]:

\[ \Delta V_a = \Delta V_c \cdot \frac{C_b}{C_a + C_b} \] (2.7)

The resulting externally measurable charge is then:

\[ Q_a = \Delta V_a \cdot C = \Delta V_c \cdot \frac{C_b}{C_a + C_b} \cdot \left[ C_a + \frac{C_b C_c}{C_b + C_c} \right] \] (2.8)

Under the assumption that \( C_b \) is usually smaller than \( C_c \), (2.3) can be simplified\(^{11}\) to [21]:

\[ Q_a = \Delta V_c \cdot C_b \] (2.9)

This charge is referred to as the apparent charge. IEC 60270:2000 [18] emphasizes the character of this measurable quantity by stating that:

\[ "The apparent charge is not equal to the amount of charge locally involved at the site of the discharge, which cannot be measured directly." \]

The previously introduced capacitive equivalent circuit has been criticized by different authors [80]–[82]. There are basically two main points of criticism. The first is related to the concept of capacitance. According to [81] a void is not an equipotential surface and therefore, cannot be described by means of capacitance. Boggs [80] questions the idea behind capacitance without electrodes. However,

\(^{11}\)This assumption leads to \( C = C_a + C_b \).
the second and even more important aspect is the inability to reflect the properties of a gas discharge by means of a capacitance [82]. Pedersen et al. have put forward a series of papers where they derived a new model that is based on the concept of induced charge [83]–[85]. The general idea behind this model will be reproduced here based on the following considerations: If a discharge inside of a void takes place then free charges in form of electrons and ions will be present inside of the void after the discharge is quenched. They will be deposited on the cavity surface and space charges will remain in the cavity [83]. Based on these assumptions a charge will be induced to the electrodes, which is given by [83]:

\[ q = -\iiint_{\Omega} \lambda \rho d\Omega - \int_{S} \lambda \sigma dS \]  \hspace{1cm} (2.10)

with

- \( \Omega \). volume of the complete dielectric
- \( \rho \). volume charge density
- \( S \). surface of the void
- \( \sigma \). surface charge density

and \( \lambda \) being a dimensionless scalar function that depends on the position of the void. A comprehensive description of \( \lambda \) and how it is obtained can be found in [83]–[85]. However, to calculate the charge, which flows through the leads as a consequence of a discharge in the void, Pedersen associated the deposited charge on the cavity surface and the induced charge on the electrodes with an electric dipole. The resulting dipole moment can be calculated by [83], [84]

\[ \vec{\mu} = \int_{S} \vec{r} \sigma dS \]  \hspace{1cm} (2.11)

with

- \( \vec{r} \). radius vector to determine the position of the surface.

In the former equation the influence of space charges in the void have been neglected. The corresponding induced charge is thus given by:

\[ q = -\vec{\mu} \cdot \vec{\nabla} \lambda \]  \hspace{1cm} (2.12)

Lemke [82] as well as Hauschild and Lemke [79] established the dipole moment.
by assuming a uniform field arrangement that is composed of point like charges between two dielectric layers with plane electrodes. The movement of charges is hindered by the dielectric layers, which are separated by distance $d_c$. The charges are due to electrons and positive ions that are generated during an electron avalanche. The authors argued that the energy, $W_a$, which is transferred by an electron avalanche that ignites at inception voltage, $V_i$, is given by

$$W_a = V_i \int_0^{t_d} i_a(t) \, dt = V_i \cdot q_a = e \cdot n_i \cdot d_c \cdot E_i$$  \hspace{1cm} (2.13)$$

with

- $i_a(t)$...current in the external circuit
- $t_d$...discharge duration
- $q_a$...charge flowing through the external circuit
- $e$...elementary charge
- $E_i$...inception field strength
- $n_i$...number of ionized molecules

The included dipole moment is then given by

$$\mu = e \cdot n_i \cdot d_c.$$  \hspace{1cm} (2.14)$$

Equation (2.13) can be rearranged for the charge that is delivered to the electrodes.

$$q_a = e \cdot n_i \cdot d_c \cdot \frac{E_i}{V_i}$$  \hspace{1cm} (2.15)$$

Lemke [82] as well as Hauschild and Lemke [79] furthermore, state that despite the claim in IEC 60270:2000 [18] that the apparent charge is not equal to the charge locally involved at the site of the discharge, the external charge is a measure of the internally involved charge. Today there is still an ongoing discussion towards the capability of the capacitive equivalent model [86], [87].

However, even if the charge might not be correctly represented by the capacitive PD model, it is still able to accurately describe the voltage distribution across the test sample. It is hence possible to acquire information about the phase of discharge occurrence as related to the phase resolved partial discharge representation. To further illustrate this, an alternating voltage, $\hat{v}_{0ac} \cdot \sin(\omega t)$, will be
applied to a solid dielectric containing a void. The voltage is then capacitively divided and the voltage across the void in the absence of discharges becomes

\[ V_{c0}(t) = \hat{v}_{0ac} \cdot \frac{C_b}{C_b + C_c} \cdot \sin(\omega t). \]  \hspace{1cm} (2.16)

It is further assumed that whenever the voltage across the void reaches the inception voltage, \( V_{inc} \), a discharge ignites and the voltage drops down to the residual voltage, \( V_{res} \). Under these circumstances the voltage across the void in case of discharges, \( V_{cd}(t) \), behaves as depicted in Figure 2.6.

![Figure 2.6: Voltage across a void inside of a solid dielectric in case of discharge activity and no discharge activity.](image)

As previously stated, the capacitive equivalent circuit is only valid at alternating voltages. In this thesis the main focus is on direct and combined voltages. Nevertheless, the capacitive equivalent can also be used at direct voltages if the capacitors are extended by parallel resistors [21], [88], [89] as shown in Figure 2.7.
Figure 2.7: Solid dielectric with a gaseous intrusion a) and corresponding capacitive-resistive equivalent circuit b). Adapted from [21].

The capacitor \( C_c \) represents the gas filled void inside of the solid dielectric. \( C_b \) is the part of the dielectric in series to the void and \( C_a \) is the healthy part of the dielectric. The resistors represent the finite conductivity of the dielectric. \( R_b \) is related to the volume resistance of the dielectric in series with the void and \( R_c \) is due to the surface resistivity of the void. \( R_a \) represents the resistivity of the healthy part of the dielectric.

If a direct voltage, \( V_{0dc} \), is applied to the previously described system it will be distributed according to the values of the different capacitors and resistors, which represent the dielectric properties including the dimensions of the void. Furthermore, the application of the voltage, \( V_{0dc} \), is comparable to a switching process and hence a differential equation has to be evaluated to model the voltage behavior \( v_{cde} \) from turn on of the voltage until the steady state. According to Densley [89] the voltage across the void, when no discharges occur, can be given as

\[
v_{cde} = V_{0dc} \frac{R_e}{R_b + R_c} + V_{0dc} \left( \frac{C_b}{C_b + C_c} - \frac{R_e}{R_b + R_c} \right) \cdot e^{-\frac{t}{\tau}},
\]

where

\[
\tau = \frac{R_b \cdot R_c \cdot (C_b + C_c)}{R_b + R_c}.
\]

A discharge can occur if the voltage \( v_{cde} \) is higher than the inception voltage, \( V_i \), which is the voltage that has to be reached to give a starting electron the required
energy on its free path to cause ionization. After a discharge has occurred the voltage across the cavity drops to a value, which is referred to as residual voltage, $V_{\text{res}}$, [31] or remanent voltage [89]. Due to the introduction of a residual voltage the starting condition required to solve the differential equation that describes the voltage across the cavity has changed. This leads to a modified version of (2.17), which has also been given by Densley [89]:

$$v_{\text{dcdc}} = V_{\text{resdc}} \cdot e^{-\frac{t}{\tau}} + V_{\text{dcd}} \frac{R_c}{R_b + R_c} \left(1 - e^{-\frac{t}{\tau}}\right)$$

(2.19)

Densley also extended the presented case to a dc signal being superimposed by a single frequency ac signal.

$$v_{\text{cdcac}} = v_{\text{dcd}} + \frac{C_b}{C_b + C_c} \cdot \sin(\omega t)$$

(2.20)

In Section 2.2 different forms of discharges have been described depending on the field strength at fixed geometry. In the case of internal PD at ac voltages three different forms of discharges have been reported in the literature. These are according to Morshuis [90] the Townsend-like discharge, the streamer-like discharge and the pitting discharge. In [90] it was reported that the discharge mechanisms change after prolonged discharge activity i.e an ageing of the test sample. The first stage is governed by the streamer-like discharge, the second stage corresponds to the Townsend-like regime and the third stage to the pitting mechanism. Morshuis further indicated that higher voltages lead to significantly reduced transition times between the discharge modes. The terms Townsend-like and streamer-like discharge have been introduced and extensively studied by Devins [91]. The Townsend-like discharge current appears somehow symmetrical with a flat top and longer pulse duration as compared to the streamer-like discharge. It is governed by the Townsend mechanism. The streamer-like discharge in turn is characterized by fast rise times and large peak values and is mainly driven by photoemission [92]. Devins furthermore introduced the term overvoltage, which describes the difference between discharge inception voltage and the actual breakdown voltage of the void. The occurrence of an overvoltage can be explained with the unavailability of starting electrons at the time instance when the inception voltage is reached. As the external voltage usually increases further during the waiting time for a starting electron, the breakdown
voltage can be higher as the inception voltage. Devins experimentally verified that Townsend-like discharges are related to low overvoltages and streamer-like discharges are related to high overvoltages. Morshuis and Kreuger [93] argued that the streamer-like discharge, is the dominant discharge in a dielectric bound void due to the low secondary emission coefficient of the dielectric. The authors further indicated that a discharge by-product layer on the voids surface is required for a transition from streamer-like to Townsend-like discharge. These by-products will enhance the availability of secondary electrons. Fromm [31] reported the existence of Townsend-like and streamer-like discharges for dc voltages. He concluded a higher Townsend-like discharge probability for dc voltages than for ac voltages. The term pitting discharge was introduced by Morshuis [90]. The discharge appearance is characterized by very small pulse amplitudes and high discharge frequencies. A prerequisite for this type is the formation of crystals at the voids surface, which lead to a local field enhancement.

2.4 Surface discharge

So far metallic electrodes separated by a gaseous dielectric, commonly referred to as corona and electrodes being separated by solid dielectrics containing gaseous intrusions have been discussed. Another typical electrode arrangement consists of electrodes, which are separated by a healthy dielectric where the tangential field stress i.e. the field stress parallel to the dielectric surface [21] plays an important role. An exemplary electrode configuration is illustrated in Figure 2.8. This type of discharge is referred to as a surface discharge and forms a subcategory of dielectric barrier discharges [94], [95]. Küchler [38] emphasizes the importance of surface discharges for high voltage engineering due to the sheer amount of surfaces, their weak dielectric strength and the strong erosive influence. If an alternating voltage is applied to a surface discharge arrangement an equivalent circuit according to Figure 2.8 can be used to describe the discharge behaviour [21], [38], [96]. Due to the similarity to the internal PD equivalent circuit there is no doubt that the discharge occurrence will also be quite similar. Consequently, Mason [96] points out that surface discharges will ignite mainly during the rise of the alternating voltage.
A voltage distribution which corresponds to a capacitive equivalent circuit as per Figure 2.8 a) has been given by Halleck [97]. The voltage across the capacitor, which represents the gaseous part, $V_{c1}$, is given by

$$V_{c1} = \left( \frac{1}{1 + \frac{d_2}{\varepsilon_2 d_1}} \right) \cdot V_0$$

(2.21)

where $d_2$ is the thickness of the solid dielectric, $d_1$ is the thickness of the gaseous part, $\varepsilon_2$ is the permittivity of the solid dielectric and $V_0$ is the voltage between the point and the plane electrode.

If a dc voltage i.e. stationary flow field, is considered an equivalent circuit as per Figure 2.8 b) applies. $R_1$ represents the surface resistance of the solid dielectric, which might be influenced by pollution. $R_2$ is the volume resistance of the solid dielectric.

Küchler [38] points out that the development of surface discharge is again field strength dependent and therefore, different phenomena can be observed if the field strength is varied. At first a glow discharge can be recognized if the electrode radius of curvature is small. In any other case the first observed discharges are streamers, which ignite in the air gap and traverse along the surface of the solid dielectric. The travel distance of the streamers is governed by the applied stress, the polarity and the capacitance of the dielectric [95]. This discharge mechanism is following glow discharges if those were the first to be observed. What makes surfaces discharges extremely critical is the possibility of leader discharge inception at very short distances as compared to solely gas based dielectric.
arrangements. This is caused by the much higher currents, which enable thermal
tonization in the streamer region due to the large capacitances of the dielectric
[38]. Akishev et.al. [98] have shown for surface dielectric barrier discharges that
are caused by a negative impulse voltage of a duration of longer than 1 µs that
the discharge starts with streamers, which can transform into leader channels
with a streamer zone at their head. Those streamers can form into new sections
of the leader channel, where again streamers can ignite and so forth.

2.5 Summary

In this chapter the different sources of partial discharges and their underlying
physical mechanisms have been explained. The relevant gas discharge mecha-
nisms given are the Townsend discharge, the streamer discharge and the leader
discharge. Based on the electrode arrangement three types of partial discharges
have been distinguished. These are corona, surface discharges and internal dis-
charges. Their different forms of appearance and the physical mechanisms have
been presented. In the next chapter the measurement principle and the utilized
measurement system is described.
3 Analysis method and test setup

In this chapter the methodology of the research carried out is described. It starts with a summary of existing dc partial discharge evaluation methods as presented in Section 3.1 and continues with a description of the proposed analysis method in Section 3.2. The measurement setup is explained in Section 3.3. This chapter closes with information on the test samples in Section 3.4.

3.1 Existing dc partial discharge evaluation methods

The detection and measurement of partial discharges is one important step towards the analysis and interpretation of the effects of such discharges on the lifetime of dielectrics as well as on the revelation of the underlying physical processes. In general partial discharges are characterised by their electrical pulses and their measurable and derivable quantities. One property, the (apparent) charge, \( Q \), has found acceptance as the most significant quantity in characterizing PD activity [17]. Therefore, it is the apparent charge, which is recorded by a PD measurement system. Depending on the data acquisition unit and the involved post-processing, many different quantities related to the charge or derived from the charge can be gathered. Gulski and Kreuger [99] sorted these quantities into three different categories, which are:

1. Basic quantities (measured during one cycle of the voltage)
2. Deduced quantities (derived from basic quantities during multiple cycles)
3. Statistical operators (used for statistical treatment of deduced quantities)

For alternating voltage a measuring concept that relates the time of discharge occurrence to the phase of the voltage proved useful. An early introduction of this method was presented in a paper by Fruth et al. [100], where they proposed
a three dimensional representation for partial discharge diagnosis. The quantities used are the charge, $Q$, deduced from integration in the frequency domain and the number of PDs, $n$, of a discrete charge level, where both are related to the phase angle, $\varphi$, of the applied voltage. Due to the phase angle relation the concept is called phase resolved partial discharge analysis (PRPDA or mostly PRPD). As the data used can be measured during one cycle of the test voltage, PRPD is solely composed of basic quantities.

However, for direct voltage no agreed standard exists and many different methods have been developed throughout the years of PD detection and evaluation under direct voltage conditions. These methods range from relying on basic quantities over derived quantities to stochastic measures and combined approaches. In literature the following evaluation methods can be found:

- discharge frequency as a function of time [29]
- number of discharges as a function of the discharge magnitude [39]
- discharge frequency as a function of the discharge magnitude [101]
- mean magnitude of and average time to successive discharges as well as average time to a previous discharge as a function of the discharge magnitude [31], [102]
- discharge magnitude and time between (successive and previous) discharges as a three dimensional histogram [31]
- empirical moments (e.g. skewness, kurtosis, variance) of discharge magnitude and time between discharges distributions [103]
- empirical moments (e.g. skewness and kurtosis) of PD pulse parameters (e.g. amplitude, rise time and fall time) [104]
- Weibull scale parameter $\beta$ for discharge magnitude and time between discharges distributions [103]
- charge difference or time difference to a successive discharge as a function of the time difference or the magnitude difference to a previous discharge as a three dimensional histogram [2], [105]
- time difference to previous discharge as a function of the charge difference to a previous discharge as a three dimensional histogram [2], [105]
One challenge in the area of PD detection at dc is the separation of PD signals and noise as well as multiple PD sources from each other. Therefore, many of the previously introduced evaluation methods use additional pre-processing procedures. One of which is pre-sorting of pulses due to their pulse shape by means of TF map [40], [103].

The aforementioned methods have in common that they cannot be as easily applied as the well-known PRPD method. For example the discharge frequency as a function of time has the disadvantage that a precise knowledge of the materials involved and potential discharge locations is required to enable a defect identification. It has been indicated that many test methods rely on time and magnitude differences of discharges. All of these methods have in common that their ability to distinguish between different defects is strongly influenced by the number of simultaneously active defects. If for example a source with a low repetition rate and a fast repetition rate is active then the defects might not be distinguishable nor might they be identifiable. Hence, those methods are impracticable for tests containing multiple discharge sources and for tests outside of laboratory environments.

3.2 Phase resolved partial discharge analysis at dc voltage

As it is the aim of this thesis to transfer the approach of PRPD to dc PD measurements, a modified version of the ac PRPD method is used for the evaluation of discharges. In general PRPD requires a synchronisation to a repeating sequence, which in case of an ac voltage is simply the applied voltage. When a dc voltage without any sinusoidal components is used, then synchronization is not possible and hence PRPD cannot be used. To overcome this problem a repeating sequence has to be superimposed to the dc voltage. This repeating sequence has to be present as an additional voltage component and is due to the required periodic character always an ac component. To obtain a repeating sequence different approaches are valid. At first a single net-frequency sinusoid could be added to the direct voltage. This approach has been recently used to analyse converter-transformers i.e. [106]. Another possibility is to add single sinusoidal components of various frequencies [107]. Furthermore, artificially generated dc
voltage waveforms that contain a repeating sequence have recently been proposed to enable PRPD [108], [109]. The former methods have the major drawback that the dc character of the obtained patterns and the underlying discharges is questionable. Nevertheless, the by far easiest approach is to make use of the way how dc voltages are generated [110]. Speaking of generation in the context of dc voltage might be a bit misleading as except from photovoltaic cells or fuel cells dc is simply not generated but obtained from ac by means of rectification.

Rectifying circuits in general can be divided into line commutated converters (LCC) and voltage sourced converters (VSC). LCC circuits are mainly based upon diodes and thyristors, whereas VSC circuits rely on IGBTs. Even though, their switching philosophies are completely different they share one common aspect. This is the presence of harmonics, which are also known as ripple, on the obtained dc voltage. This ripple, consisting of whatever harmonics, in fact is a repeating i.e. periodic sequence, which can be used by means of synchronisation for PRPD. The periodic character of the ripple is further emphasized in the definition of ripple according to IEC 60060, which shall be reproduced here:

"periodic deviation from the arithmetic mean value of the test voltage"

[111]

This is continued by defining the ripple amplitude as:

"half the difference between the maximum and minimum values" [111]

Based on these definitions it has been decided that two different quantities of ripple are used in this thesis. One, which is called ripple voltage, represents the instantaneous value of the ripple i.e. the dc component, $\bar{V}$, is subtracted from the instantaneous value of the voltage, $V(t)$. It is mathematically expressed as:

$$\Delta V_{dc} = V(t) - \bar{V}$$

(3.1)

with

$\bar{V}$ ......... mean value of the voltage

The other value is related to the amplitude of the ripple and quantifies the deviation of the voltage amplitude, $\hat{V}$, from the mean value in percent. This is
meant, when the terms 'amount of ripple', 'voltage ripple', 'level of the ripple' or simply 'ripple' are used in this thesis.

\[ VR\% = \frac{|\hat{V}| - |\bar{V}|}{|\bar{V}|} \times 100\% \]  \hspace{1cm} (3.2)

Some of the presented quantities are graphically illustrated in Figure 3.1.

Figure 3.1: One period of a dc voltage that is obtained by a half-wave rectification of an ac voltage with an arbitrary period, \( T \). The mean value, \( \bar{V} \), and the peak value, \( \hat{V} \) are indicated.

The above statements indicate that no modification to the dc voltage is necessary as the ripple is naturally present. Nevertheless, this is not completely accurate because of two limiting aspects that have to be considered. First of all if a view is taken from the power system operation side then a ripple on the dc voltage is usually not intended. The dc side of the transmission system is therefore equipped with harmonic filters. These filters are able to limit the harmonic content or completely eliminate dominant harmonics. This leads to the second aspect, which are the occurring harmonics and the resulting combined voltage signal. Here, one has to decide whether it is useful to synchronize the PD detection to the whole sequence or a single harmonic, usually the base frequency. In this thesis it has been decided to use the net frequency for the following reasons:

As the harmonic content of the voltage signal is directly related to the rectifier technology used, it might change from application to application. The resulting dc voltage will therefore appear differently in terms of waveform. Even though,
the harmonic content may vary, one frequency will be persistent. This is the fre-
quency of the ac signal that has to be rectified, which is usually the net frequency
of either 50 Hz or 60 Hz. Persistent must not be misinterpreted as occurring as
e.g. if a six-pulse converter is considered the first occurring harmonic is of 6th
order i.e. six times the base frequency. With a net frequency of 50 Hz this results
in 300 Hz. It is the authors opinion that the 300 Hz component will, from the
discharge side, act as 6 times 50 Hz and therefore, result in 6 concentrations of
discharges, if 50 Hz is used as the synchronisation frequency. A physical expla-
nation for this postulation can be found, when the discharge inception voltage is
considered.

![Figure 3.2: Postulated relation between synchronisation frequency and discharge
centration. Synchronisation is set to 50 Hz in a) and 300 Hz in b).]

Reaching the inception voltage, $V_{inc}$, as indicated in Figure 3.2 enables the
ignition\textsuperscript{12} of a discharge. In the case of a voltage that is composed of a direct
voltage and a 300 Hz sinusoid as shown in Figure 3.2 a) the inception voltage
will be reached at least six times with respect to a 50 Hz period. A recording of
the discharge activity over a longer time period would result in a concentration
of discharges in six spots. If the same recording would be performed with a
synchronization frequency of 300 Hz than the six spots would merge into one
spot as indicated in Figure 3.2 b).

The former idea is supported by experimental data of Judd et. al. [112].

\textsuperscript{12}For simplification reasons it is assumed that a starting electron is always available.
3 Analysis method and test setup

In their publication tests are presented using a dc voltage that is superimposed with a 300 Hz signal. Even though, it is stated that a synchronisation to 300 Hz (3.3 ms) has been performed, a time window of 8 ms and approximately two full-waves and a quarter wave i.e. 125 Hz as well as three concentrations of discharges are shown. Nevertheless, if these results would be mapped onto a 50 Hz synchronisation one could expect six concentrations of discharges or one concentration if 300 Hz is used. The following rule for dc PRPD synchronisation could be drawn from these considerations:

If the dominant harmonic is a multiple of the net frequency one might always synchronize to the net frequency under the drawback of having the dominant harmonic order times the number of discharge concentrations.

Based on the former explanation 50 Hz has been chosen as the synchronization frequency throughout this thesis.

3.3 Test circuit and measuring devices

All measurements are performed using a test-stand that has an equivalent circuit as per Figure 3.3.

![Figure 3.3](image)

In general the circuit, which has been set-up with construction kit parts manufactured by MWB, is a half-wave rectifier with a smoothing capacitor. The circuit can be divided into two parts according to the dominant voltage type. These are the ac-side and the dc-side. The ac-side consists of a transformer, a coupling
capacitor, $C_{k1}$, which is used for the synchronization, S. The synchronization is performed with a quadripole CPL 452 and a first MPD 600, both manufactured by OMICRON. The inductivity, $L$, serves as a low-pass filter designed to decouple the ac-side from the dc-side during discharge activity at the test object. The dc-side consists of two diodes, to reduce the individual voltage drop per diode, a load resistor, $R_L$, a 1200 pF coupling capacitor, $C_{k2}$, for the decoupling of the partial discharge signal, PD, and the test object, TO. The RC combination of $R_L$ and $C_{k2}$ forms a time constant, $\tau_L$, that mainly determines the ripple of the dc voltage. The term mainly is used as for example every resistive component, contributes to the resistive part of the time constant, such as the voltage divider for the measurement of the voltage on the dc-side. This voltage divider is composed of the two resistors $R_{M1}$ and $R_{M2}$. To minimize its influence $R_{M1}$ is chosen to 1 GΩ. $R_{M2}$ is the 1 MΩ input impedance of a HBM GN 110, which is used to measure the dc voltage, $V_{dc}$. A 1 kΩ shunt resistor, $R_S$, is used to measure the current through the test object, $I_{TO}$. Finally, an additional smoothing capacitor, $C_S$, can be added depending upon the desired ripple. Table 3.1 gives an overview of the used ripple values and the corresponding resistor-capacitor combinations.

<table>
<thead>
<tr>
<th>$C_{k2}$ / nF</th>
<th>$R_L$ / MΩ</th>
<th>$C_S$ / nF</th>
<th>$V_{R%}$ / %</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.2</td>
<td>-</td>
<td>20</td>
<td>0.1 0.2</td>
</tr>
<tr>
<td>1.2</td>
<td>280</td>
<td>10</td>
<td>0.4 0.5</td>
</tr>
<tr>
<td>1.2</td>
<td>140</td>
<td>10</td>
<td>0.6 0.7</td>
</tr>
<tr>
<td>1.2</td>
<td>140</td>
<td>6</td>
<td>0.8 1.1</td>
</tr>
<tr>
<td>1.2</td>
<td>-</td>
<td>-</td>
<td>1.2 1.9</td>
</tr>
<tr>
<td>1.2</td>
<td>280</td>
<td>-</td>
<td>2.6 3.6</td>
</tr>
<tr>
<td>1.2</td>
<td>140</td>
<td>-</td>
<td>4.4 5.5</td>
</tr>
<tr>
<td>1.2</td>
<td>70</td>
<td>-</td>
<td>8.1 9.2</td>
</tr>
<tr>
<td>1.2</td>
<td>20</td>
<td>1.2</td>
<td>13.5 13.8</td>
</tr>
<tr>
<td>1.2</td>
<td>20</td>
<td>-</td>
<td>24.5 26.4</td>
</tr>
<tr>
<td>1.2</td>
<td>10</td>
<td>-</td>
<td>48.0 49.5</td>
</tr>
</tbody>
</table>

The PD signals are decoupled with a quadripole CPL 452 manufactured by OMICRON. It contains an inductivity, an ohmic resistor and a capacitor. The quadripole transforms the PD current pulses into a voltage, which is subsequently transformed into a charge with a MPD-600 manufactured by OMICRON. The
combination of quadripole and MPD-600 is referred to as PD-detector in this thesis. It is indicated by PD in the equivalent circuit as per Figure 3.3. The charge is obtained via a quasi-integration that is performed in the frequency domain due to a bandpass filtering of the current pulses. The filter characteristics are set to have a lower limit frequency of $f_1 = 100$ kHz and an upper limit frequency $f_2 = 400$ kHz, which is in accordance with IEC 60270. For a better evaluation of the physics behind partial discharges an additional measurement of the original discharge pulses in the ground loop of the test object is performed. The current is measured using a 1 kΩ shunt resistor in combination with a HBM Gen7t transient recorder equipped with GN110 probes. The connection between the probes and the transient recorder is performed via optical fibres. The system can provide up to 100 MS/s at a resolution of 14 bit and a rise time of 14 ns. This combination is referred to as the pulse-detector in this thesis. It is indicated by $I_{TO}$ in the equivalent circuit as per Figure 3.3. The connection between the shunt resistor and the GN110 is provided by 0.5 m long unshielded cables. Their inductance has been approximated to be between 1.5 $\mu$H and 2.0 $\mu$H.

It has been reported that different rise times exist depending on the active discharge mechanism and the dielectric configuration. For example Morshuis and Kreuger [93] reported rise times of 5 ns to 10 ns for streamer-like discharges in voids of 1 mm height and 40 mm diameter in solid dielectrics. Morshuis [90] indicated rise times in the range of some hundred picoseconds up to several ns for void heights between 30 $\mu$m to 3.7 mm. In a more recent paper [16] Bartnikas pointed out that there have been reports of discharges with rise times in the range of 1 ns to 2 ns but that those are not the dominant rise times. Luczynski [113] reported a rise time of about 40 ns for discharges inside of a cavity which have been called "slowly developing partial discharges". Bartnikas and Novak [92] recited experiments conducted by Hudon et. al. [114] with epoxy resin coated electrodes with an interspacing of 0.5 mm, where a rise-time of 20 ns for a streamer-like and 70 ns for a Townsend-like discharge have been reported. This void height is identical to the height used in this thesis and hence, similar rise times can be expected. Gravendeel [115] reports a Trichel pulse rise time of 1.15 ns for a pressure of 1 bar, 5 mm electrode inter spacing and a point radius of 12.5 $\mu$m. Dordizadeh [116] reported an average rise time of 49 ns for experiments

The interested reader is referred to the book of König [17] for further details.

It is the authors opinion that those are identical with the Townsend-like discharge type.
with a gap spacing of 6 mm to 30 mm and point radii of 19 \( \mu \text{m} \) to 55 \( \mu \text{m} \). Here, the electrode interspacing is comparable to the one used in this thesis and consequently similar rise times are to be expected. Nasser [56] gives rise times of 20 ns to 40 ns for positive streamers in point to plane arrangements. The former treatment indicates that the transient recorder used provides sufficient measuring capabilities for the test samples.

A second aspect in relation to the measurement of the discharge current is the time constant of the measuring circuit, \( \tau_m \). This time constant should be lower than the time constant of the measured discharges [90]. To approximate the time constant the equivalent circuit of the measurement setup, as shown in Figure 3.4 is used.

![Resistive capacitive equivalent circuit of the test setup.](image)

The circuit consists of a current source, which represents the discharge current, \( I_d \), a capacitor, which represents the test object as viewed from the discharge pulse, \( C_T \), the coupling capacitor, \( C_k \) and the measuring resistor, \( R_m \). The corresponding time constant can be given as:

\[
\tau_m = R_m \cdot \frac{C_TC_k}{C_T + C_k} \tag{3.3}
\]

It is evident from (3.3) that the influence of the coupling capacitor is negligible due to the series connection of \( C_k \) and \( C_T \). The time constant is hence mainly governed by the product of \( R_m \) and \( C_T \). The capacitance of the test object for internal partial discharges has for example been calculated to 1.2 pF. The time
constant of the measuring circuit is then 1.2 ns. This time constant is below the maximum resolution of the measuring device. Hence, the rise time of the measuring device of 14 ns is the limiting factor.

As the tests have not been carried out in an encapsulated vessel the ambient conditions changed depending on the daily weather conditions. Those might influence the discharge behaviour as it is for example known from corona measurements that especially the air pressure and the humidity have an influence on the inception voltage [117], [118]. Therefore, the relative humidity, the air pressure and the temperature are given in each paragraph. The ambient conditions have been logged in the vicinity of the test object.

### 3.3.1 Analyses method for the discharge behaviour

In the previous section it has been argued that a periodic i.e. ac signal has to be present on the dc signal to enable the use of PRPD. If Subsection 1.1.2 is reconsidered then it is obvious that this introduced modification will result in a permanent\(^{15}\) shift of the electric field from a dc behaviour to a mixed field behaviour. The modification might therefore be associated with a possible change in discharge behaviour. Bringing these considerations together gives rise to the following requirement for the use of PRPD at dc voltage [119]:

The signal has to be modified in such a way that it contains a repeating sequence, while maintaining the general dc discharge behaviour.

To ensure the dc discharge behaviour it is necessary to evaluate the influence of the ripple on characteristic discharge properties. The quantities available for comparison based on data recorded with the PD-detector are the recorded magnitudes per discharge i.e. apparent charge, \(Q\), and their time of occurrence, \(t_i\). The PD-detector and its quantities bare the drawback of an unknown noise influence and possible integration errors resulting from the quasi-integration. These integration errors can lead to a change of the polarity of the charge and the noise could lead to misinterpretations of the discharge behaviour. However, as no experience with PRPD at dc exists the identification of noise and errors is not fully yet investigated.

The pulse detector offers a large variety of current and time related aspects.

\(^{15}\)Permanent is essential as during turn on of the voltage a dc field does also behave like a combined field.
The advantage of the pulse detector is that noise can be identified due to a visual inspection of the pulse shape. Therefore, it are the quantities that can be derived from the recordings of the pulse detector that are most suitable for an evaluation of the discharge behaviour. In this thesis it has been decided to use four pulse parameters. These are the discharge frequency, \( f_d \), the average pulse amplitude, \( \bar{i}_p \), the average pulse rise time, \( \bar{t}_{\text{rt}} \), and the average pulse fall time, \( \bar{t}_{\text{ft}} \). The discharge frequency is defined as the reciprocal of the number of discharges per second. The definitions for the other three quantities are indicated in Figure 3.5. All four values are obtained at different voltages and values of the ripple for corona discharges, surface discharges and internal discharges. The results for a given voltage and ripple are always presented as a mean value and the corresponding standard deviation, which are calculated from the recorded time series of the discharge current.

Based on the results a maximum tolerable ripple for a dc like behaviour is determined. The corresponding PRPD patterns are evaluated at a ripple that is equal to or below this value.

![Discharge current pulse parameters](image)

**Figure 3.5**: Discharge current pulse parameters.

### 3.4 Samples

In this section the different test samples used for the evaluation of corona, internal discharges and surface discharges are presented. For corona measurements in air a point to plane setup with variable point radius, \( r_N \), and variable electrode inter-
spacing, $S$, according to Figure 3.6 is used. The electrodes are made of stainless steel and their radius is about 0.5 mm. The electrode interspacing has been set to 30 mm. The plane electrode is Rogowski shaped [120] and has a diameter of 15 cm. The test stand is not encapsulated.

![Figure 3.6: Point to plane arrangement with geometric dimensions.](image)

3 Analysis method and test setup

Internal partial discharges are evaluated with a test sample that is composed of three sheets of solid dielectric material. A hole has been drilled in the middle layer to form an artificial cavity. Such a test sample has for example been used by [31], [90]. The material used is laminated paper type PF CP 201 with a dielectric constant, $\varepsilon_r$, of 5. The diameter of the void, $d_v$, is 5.5 mm and the combined thickness of the three sheets, $d_s$, is 1.5 mm. The sample length and the width, $d_e$, is 70 mm. To prevent surface discharges the test sample has been placed in an oil vessel. The oil used is MIDEL 7131, an ester oil. A corresponding scheme of the test arrangement is depicted in Figure 3.7.

![Figure 3.7: Internal discharge arrangement with geometric dimensions.](image)

Surface discharges were investigated using a point to plane setup with a solid dielectric between the electrodes. The electrodes are identical to the ones de-
scribed by Figure 3.6. The solid dielectrics are rectangular plates of length, $l$, and diameter, $d$. The samples were made of laminated paper type PF CP 201 with a dielectric constant, $\varepsilon_r$, of 5, a diameter of 0.5 mm and a length and width of 70 mm. A scheme of the arrangement is shown in Figure 3.8.

![Figure 3.8: Surface discharge arrangement with geometric dimensions.](image)

### 3.5 Summary

In this chapter different, existing partial discharge evaluation methods for dc voltages have been presented. They all have in common that they are not as easy applicable as the well-known ac PRPD method. Hence, the requirement for a new method similar to PRPD for dc PD purposes is given. The newly proposed method uses the ripple, which is always present on dc voltages due to the rectification process. The ripple, or its fundamental frequency, serves as the required repeating sequence. The introduction of a new method creates a challenge and an opportunity. The opportunity is the availability of a method as powerful as the ac PRPD method. The challenge however lies in the quantification of the maximum tolerable ripple and the derivation of characteristic patterns for PD source identification purposes. The first challenge is dealt with by analysing the current that is associated with partial discharges. It is evaluated how this current is influenced by the ripple on the dc voltage. The measurement system that is used for this task has been described in this chapter. The second challenge is approached by recording characteristic phase resolved partial discharge patterns using a commercially available PD measuring system. The test equipment also has been given in this chapter. In the next chapter the proposed measurement principle is applied to a point to plane arrangement.
4 Corona in air

This chapter presents the behaviour of a point to plane arrangement that is subjected to a dc voltage that has been obtained by a half-wave rectification. In Section 2.2 different discharge mechanisms with respect to point to plane arrangements have been explained. The aspect that is mainly responsible for the different mechanisms is the voltage polarity. Hence, the examination is subdivided into tests with negative polarity and positive polarity. The corresponding results and discussion are presented in Section 4.1 and Section 4.2, respectively. The structure of both sections is identical and is as follows: Firstly, the test object is stressed with a constant peak value of the dc voltage, while the ripple is varied. These tests are performed to evaluate the ripples influence on the discharge behaviour. The corresponding procedure, results and discussion are given in Subsection 4.1.1 for negative polarity and in Subsection 4.2.1 for positive polarity. Secondly, the same test arrangement is stressed at a fixed ripple and characteristic phase resolved partial discharge patterns for negative and positive corona are obtained. The patterns and their physical cause of formation are explained in Subsection 4.1.2 and Subsection 4.2.2.

4.1 Negative corona in air

A point to plane arrangement as described in Section 3.4 is supplied with a negative dc voltage, which is obtained due to a half-wave rectification of an ac voltage. The electrode inter spacing has been set to 30 mm and a point with 0.5 mm radius has been used. A schematic representation of the test sample is given in Figure 3.6. The equivalent circuit and the used measuring devices are described in Section 3.3.
4.1.1 Influence of the voltage ripple on the discharge behaviour

To study the influence of the voltage ripple on the discharge behaviour of negative corona the point to plane arrangement has been stressed with a constant peak value, $\hat{V}$, of the voltage, while the ripple, $V_{R\%}$, was varied. Variation of the ripple has been achieved due to a change of the smoothing capacitor or the load resistor. The corresponding combinations are listed in Table 3.1. The ambient conditions were a relative humidity of 33 %, a temperature of 20 °C and an air pressure of 995 hPa. All environmental data is given as average values over the whole measurement duration.

To evaluate the influence of the ripple the discharge frequency, $f_d$, the average pulse amplitude, $\bar{I}_p$, the average pulse rise time, $\bar{t}_{rt}$, and the average pulse fall time, $\bar{t}_f$, have been recorded at two different voltage levels. The first level, which is at -25 kV, has been selected as it is above the inception voltage of Trichel pulses, which was at -19 kV at the mentioned ambient and geometrical conditions. The second level of -30 kV is below the pulseless glow inception voltage of -35 kV and highly above the onset of Trichel pulse corona. It has been decided to leave out a treatment of the influence of the ripple on the pulseless glow as this type of discharge cannot be detected with the conventional wideband partial discharge detection method, which is the underlying acquisition principle used for the PD detection in this thesis. Results for the discharge frequency as a function of the ripple at -25 kV have already been published by the author [121]. In this publication the other parameters were not evaluated and no detailed explanation for the underlying physical effects were given.

The results for the discharge frequency as a function of the voltage ripple are shown in Figure 4.1. It is evident that the discharge frequency stays nearly constant up to a ripple of 3 % at a peak voltage of -25 kV and -30 kV. Afterwards, the discharge frequency decreases almost linearly i.e. quadratic if a linear scaling is selected, with increasing ripple.
A generally higher discharge frequency at -30 kV can be observed as seen in Figure 4.1. The increase in discharge frequency as a function of the voltage is a typical feature of Trichel pulse corona and has been reported by several authors such as [62], [122]. However, no physical explanation for the reduction of the discharge frequency with an increasing ripple at a fixed peak value of the voltage is known to the author. Therefore, it shall be derived here for the first time.

An approach to obtain a physical explanation for the decrease in the discharge frequency is done by a consideration based on the inception voltage. To this end the previously evaluated discharge pulses have been examined in relation to the applied voltage. The position of the first discharge and the last discharge per 20 ms time window has been marked in relation to the corresponding voltage. Additionally, the course of the first derivative of the voltage is indicated. The corresponding results for a ripple of 4.9 %, 8.7 %, 25.5 % and 48.0 % are given in Figure 4.2.

Up to a ripple of 4.9 % the inception voltage is reached throughout the complete course of the waveform of the voltage as is shown in Figure 4.2 a). At a ripple of 8.7 % a gap in discharge activity over 3.5 ms is visible as is depicted in Figure 4.2 b). It is indicated that the start and the end of the discharge activity are at the same voltage level. This level is at -21 kV, which is above the inception voltage of -19 kV. The absence of discharges can therefore, not be argued with the inception voltage.

In Figure 4.2 c), which has been recorded at a ripple of 25.5 % another be-
Figure 4.2: Voltage, $V$, current through the test object, $I_{TO}$, and first derivative of the voltage as a function of time, $t$, at a ripple of 4.9 % a), 8.7 % b), 25.5 % c), 48.0 % d).

Behaviour is visible. Here, a significant difference between start and end of discharge activity and the corresponding voltage is recognizable. The start of discharge activity jointly happens at a turning point of the voltage, which is indicated by dV. The voltage at which the discharges ignite is at -20 kV, which is still higher than the original inception voltage. The extinction voltage of -22 kV is above the inception voltage. Figure 4.2 d) indicates that the same observation can be made for a ripple of 48.0 %. Here the ignition voltage is in the range of the inception voltage. In this case it is obvious that the discharge extinction does also fall together with a turning point of the applied voltage.

The previously presented observations clearly indicate that the reduction of discharge activity with increasing ripple cannot solely be argued with the inception voltage. Therefore, another explanation has to be found. For small values of the ripple e.g. 8.7 % the ceasing of discharge activity even though the voltage is above the inception voltage seems to be one important aspect. This behaviour could be caused by the absence of starting electrons during the corresponding time instances. The periodic nature of the absence of discharges is an argument against this hypothesis as the availability of starting electrons usually is of
stochastic nature e.g. [123].

The absence of discharges could also be a space charge driven effect. It has been argued in the theory section of this thesis that negative space charges have to travel sufficiently far away before a new Trichel pulse can commence. Hence, if a field effect would be active that impedes the movement of negative space charges i.e. keeps them in their position in the ionisation region, discharge activity would cease. It seems likely to argue that the continuous negative potential of the point electrode is the major argument to withdraw this hypothesis. However, as the applied voltage is a mixed voltage that contains a dc and multiple ac components, the influence of these voltage components might have to be treated separately. Support for this approach can be found in literature, where the influence of the frequency of the voltage on PD behaviour of different defects has been reported [124]–[126]. Hence, an analysis of the different voltage components is useful. Therefore, the voltage has been analysed with a Fast-Fourier-Transformation (FFT) to obtain the different voltage components. Based on the results a time resolved representation of the three strongest ac components of the voltage has been included into a time-series of the discharge current. For reference the voltage, as well as the inception voltage have been added.

Figure 4.3 a) shows the corresponding results for a ripple of 8.7 % and Figure 4.3 b) for 25.5 %. In the case of a ripple of 8.7 % a strong correlation between discharge absence and the positive rising of the 100 Hz as well as 150 Hz component is visible, while the 50 Hz component is still positive but decreasing. This observation implies that if the polarity of the point electrode is solely viewed from the alternating components it would have a positive sign. Negative space charges would therefore be attracted by the point electrode. The negative dc component does however indicate a constant movement of the negative space charges in the direction of the plane electrode. If both aspects are combined a reduced ion mobility should be the outcome. It is therefore the authors opinion that the absence of discharges is caused by a reduced negative ion mobility that is conditioned by the polarity reversal of the alternating voltage components of the dc voltage. At a ripple of 25.5 %\textsuperscript{16} the alignment of the components differs and hence another mechanism might be active or simultaneously active, which shall be further investigated.

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\textsuperscript{16}Only the time frame where the discharge activity ceases until the voltage crosses the inception voltage is considered.
4 Corona in air

For large ripples two aspects, which might be of importance can be identified. Firstly, the difference in ignition and extinction voltage, which only exists at large ripples and which increases with increasing ripple. Secondly, the observed agreement between turning point of the applied voltage and discharge extinction, which is also only valid for large values of the ripple. One possible reason for the first effect could be a phase shift of the voltage, which means that the position of the maximum of the voltage is not as displayed. This hypothesis can be falsified if the relative position of the maximum of the discharge current in relation to the maximum of the voltage is considered. As the voltage dependence of the discharge current is another typical feature of negative corona, the almost perfect match of current maximum and voltage maximum can be taken as a no-phase-shift indicator.

Another explanation for the observed phenomenon might be a memory effect, which has for example been reported for ac voltages and the interaction of particles, being left over from discharge processes in the negative half wave, with the discharge mechanism of the positive half wave and vice versa [127]. Due to the continuous negative potential of the point a reversal of the charge movement can be neglected. However, as a time varying component of the voltage is present in form of the ripple, the electric field is also time varying. A time varying electric field is, as introduced with Maxwell’s modification to Ampere’s Law, associated with a displacement current. If the graphs depicted in Figure 4.2 are compared with each other, it is visible that the discharge current has an underlying component that is sensitive to the dv / dt rate, which increases with increasing ripple. This component is also present during discharge activity. Mor-
row and Sato [128], showed that a discharge, which takes place in a time varying electric field has two current components. One of the components is associated with the movement of electrons, positive and negative ions, whereas the other is a displacement current. Hence, the $dv/dt$ sensitive current component will rather be a displacement current than a real movement of charge through the gap.

![Voltage, V, current through the test object, $I_{TO}$, and first derivative of the voltage as a function of time, $t$, at a ripple of 48.0 %](image)

Figure 4.4: Voltage, $V$, current through the test object, $I_{TO}$, and first derivative of the voltage as a function of time, $t$, at a ripple of 48.0 %.

A precise examination of the discharge (displacement) current has revealed that it passes the zero line and becomes positive close to the position where the discharge activity ceases as shown in Figure 4.4. Again, this current component is not caused by a movement of charge but from a time varying electric field. To create an electric field, surface charge on the electrodes is required. Due to the positive displacement current, the point has to become more positive, i.e. less negative, in contrast to its original state. Therefore, less negative charge is placed on the point and consequently the electric field is reduced. The electric field strength might then be below the inception field strength. The same applies for the observed reduced inception voltage except that the displacement current is then negative and contributes to an enhanced field strength.

Besides the introduced discharge behaviour explanation, the presence of a displacement current component is also a very good indicator to evaluate phase shifts between discharge current and applied voltage. In the prolonged case an evaluation yielded no phase shift.

The foregoing considerations lead to two conclusions with respect to the de-
crease of discharge frequency of Trichel pulse corona with increasing ripple. Firstly, the movement of negative ions is influenced by the ripple. Secondly, the ripple enforces a displacement current, which alters the electric field. Both aspects contribute to a reduction of discharge frequency with increasing ripple at a fixed peak value of the voltage.

Figure 4.5 depicts the average pulse amplitude as a function of the voltage ripple. The general trend indicates that the average pulse amplitude does slightly decrease with increasing ripple for a voltage of -25 kV up to a ripple of 3 %, whereas it stays constant up to this point for a voltage of -30 kV. For higher values of the ripple no clear relation is observable. However, an increase in standard deviation for a ripple bigger than approximately 10 % is visible, which might be related to the voltage sensitivity of the pulse amplitude of negative corona. Nevertheless, due to the large standard deviation it is not possible to make a precise statement on the relation between pulse amplitude and the level of the ripple.

As can be seen from Figure 4.6 the average pulse rise time $\bar{t}_{rt}$ seems to be independent of the voltage ripple as well as of the voltage level up to a ripple of about 10 %. Simulative experiments indicated no visual change of the pulse rise time with the voltage level [129]. The experiments of [130], [131] have shown that the rise time is independent of the averaged corona current. As the average corona current increases with increasing voltage it can be concluded that these experiments confirm the here observed independence of the rise time from the
voltage level. It has to be noted that this postulation is only true if the ripple is below 10\%. Above 10\% the mean value of the rise time as well as the standard deviation seem to slightly increase. This could again be caused by the increasing displacement current and resulting altered electric field behaviour, which influences the ion and electron movement.

![Figure 4.6: Average pulse rise time, $\bar{\tau}_{rt}$, as a function of the voltage ripple, $V_{R\%}$.](image)

The behaviour of the average pulse fall time, as illustrated in Figure 4.7, shows a sensitivity towards the voltage level. It is remarkable that the average pulse fall time is lower for -30 kV than for -25 kV, as due to the higher pulse amplitude at -30 kV one would expect an increase in fall time. A possible reason for this might be an enhanced electron and ion speed due to the higher field stress and a related faster vanishing of the particles. A second reason is that the interpretation of the data is a mirage and that no real change in fall time with the level of the voltage at least in the measured voltage range exists. This can be argued by the fall time difference between -25 kV and -30 kV in relation to the standard deviation of each of the two curves. Again, above 10\% an increase of the quantity under examination and it’s standard deviation can be observed. It is the author’s opinion that this is caused by the stronger time dependence of the electric field and the accompanied change of electron, positive and negative ion movement.
The main conclusion, which can be derived from this subsection is that the \(\frac{dv}{dt}\) stress does change the discharge behaviour and that a dc test should be carried out with a ripple below 10 %. This is further emphasized by the foregoing findings related to pulse characteristics. Furthermore, a ripple that is smaller than 3 % should be used to obtain the same discharge characteristics in terms of the pulse repetition rate and therefore the potential harmfulness of negative corona.

### 4.1.2 Influence of the voltage on the discharge behaviour

In Subsection 2.2.1 three different discharge phenomena for negative corona have been presented. These are Trichel pulses, pulseless glow and negative streamers. With regard to the proposed test method it is of particular interest whether these discharge types can be observed and if so what kind of phase resolved patterns are related to them. Evidence for the existence of Trichel pulses and pulseless glow at a ripple of 5.5 % has already been given in a paper by the author [132]. In this paper the corresponding phase resolved patterns have been presented at a ripple of 5.5 %, which is below the 10 % recommendation for pulse shape behaviour. However, in the previous subsection it has also been argued, based on the discharge repetition rate, that a ripple smaller than 3 % should be used. In a second paper by the author [121] the general applicability of the method for ripples below 3 % has been shown. Still, no complete picture from negative corona onset to breakdown with regard to the observable patterns and the underlying
physical phenomena has been given.

As the selected geometry provides a large voltage range between negative corona onset and breakdown, the ripple cannot be kept constant without changing the used passive components of the circuit. A change of components would however make a continuous measurement impossible and could introduce an additional error source due to faulty components. It has therefore been decided to use a single circuit configuration for the tests of negative corona. This configuration provides a ripple of 0.8% at negative corona onset and 1.1% before breakdown. The ambient conditions were, 23°C, 36.5% relative humidity and 1000 hPA air pressure. All environmental data is given as average values over the whole measurement duration.

The first occurring pattern, which is shown in Figure 4.8 a) is formed due to the presence of Trichel pulses slightly above discharge inception. An exemplary pulse, which has been recorded simultaneously, is depicted in Figure 4.8 b) and c). The pattern appears as a thin band of discharges, where the individual discharge magnitude is related to the time of discharge occurrence in relation to the phase angle, \( \varphi \), and therefore, to the voltage, \( \Delta V_{DC} \). The voltage level dependence of the discharge magnitude is caused by the correlation between required mean free path for ionization and the electric field strength [19], which is governed by the voltage as the geometry remains unchanged. It is evident that there is no discharge activity between 0° and 290°. This can be explained with the inception voltage and the availability of starting electrons.

![Figure 4.8: Discharge magnitude, \( Q \), and ripple voltage, \( \Delta V_{DC} \), as a function of the phase angle, \( \varphi \), recorded at -18.9 kV, a). Current through the test object, \( I_{TO} \), and voltage, \( V \), as a function of time, \( t \), b), as well as a magnified version of the current, c), which shows a Trichel pulse.](image-url)
If the voltage is further increased discharge activity takes place throughout the whole phase angle range and the discharge magnitude will increase as is shown in Figure 4.9 a). A continuous enhancement of the voltage is accompanied by two different behaviours. On the one hand the discharge magnitude and the discharge frequency increase with increasing voltage. On the other hand the discharge magnitude-instantaneous voltage dependency becomes intermittent between two modes. In the first mode the discharge magnitude is related to the instantaneous value of the voltage, which has already been described. In the second mode, the discharge magnitude seems to lose the relation to the level of the applied voltage. An exemplary $Q(\varphi)$-diagram is presented in Figure 4.9 b). It is visible that the pattern appears as an almost perfectly flat band.

![Figure 4.9: Discharge magnitude, $Q$, and ripple voltage, $\Delta V_{DC}$, as a function of the phase angle, $\varphi$, recorded at -20.3 kV. The discharge magnitudes in a) are sensitive to the voltage and insensitive in b).](image)

The intermittent behaviour could also be observed for the discharge current, $I_{TO}$, recorded in series with the test object, as is shown in Figure 4.10. It is evident that a strong influence of the voltage on the discharge current is visible in part a), whereas no influence can be seen in part b). The first recording (part a)) has been presented at a higher voltage level to show that the increase in discharge magnitude with increased voltage is mainly caused by an increase in the individual discharge current pulse amplitudes. Figure 4.10 furthermore, indicates that the discharge frequency is not only a function of the voltage. At -21.5 kV the discharge frequency has been estimated to 4.3 kHz, whereas at -20.4 kV the discharge frequency is 5.5 kHz. That means that the discharge frequency is lower at the higher voltage level. This is in contradiction to the findings of Subsection 4.1.1 and the well-known increase of discharge frequency of Trichel pulse corona.
with the voltage [62], [122]. Hence, two important aspects can be taken from the foregoing analyses. Firstly, a mechanism is active that leads to a loss of the voltage sensitivity of the discharge magnitude. Secondly, the discharge frequency seems to, at least partly, lose it’s proportionality to the voltage level. Those aspects shall now be further analysed.

Figure 4.10: Current through the test object, \( I_{TO} \), and voltage, \( V \), as a function of time, \( t \), recorded at -21.5 kV a) and -20.4 kV b).

In connection with this analysis it is noteworthy to report that a new type of discharge pulse was observed for voltages above -19.5 kV. An example of such a pulse is shown in Figure 4.11. For comparison reasons a regular Trichel pulse with almost the same pulse amplitude has been added to the figure. Both pulses have been recorded at -20.3 kV.

Figure 4.11: Current through the test object, \( I_{TO} \), as a function of time, \( t \), recorded at -20.3 kV, illustrating the occurrence of two different discharge pulses.
A visual examination reveals a strong current-time-area deviation in the pulse decay phase. This might lead to a difference in transported charge and therefore, in measured discharge magnitude in pico coulomb at identical pulse amplitude. For a possible physical explanation of the second pulse type, which is referred to as type 2 Trichel pulse in this thesis, the pulse behaviour at 2.5 µs to 3 µs is of interest. In another work [133] the author suggested that the change in gradient of the current decay, of a type 1 Trichel pulse, is associated with a negative space charge that chokes of the secondary emission, which was responsible for the current plateau in the decay phase. It might hence be concluded that no or at least a reduced secondary emission is involved in a type 2 Trichel pulse.

In his book, Loeb terms the type 2 Trichel pulses 'conditioned' Trichel Pulses [44]. He argues that these pulses are caused by a conditioning of the point cathode by ion bombardment. It is likely that the point electrode, which has been extensively used for the investigations that form the basis of this thesis has conditioned and unconditioned spots. Amin [122] associates an increased photoelectric secondary emission and a reduced secondary emission by positive ion bombardment of the cathode with the conditioned pulses. He also reasons that the negative ions build up closely to the cathode.

In Figure 4.12 a schematic is shown, which illustrates the physical processes involved in the decay phase of a type 1 and a type 2 Trichel pulse. This schematic has been constructed with support of the explanations of Amin [122]. Type 1 Trichel pulses show a decay phase that is governed by secondary emission. The emitted electrons travel into the gap, which has a reduced field strength behind the ionization zone due to the presence of positive ions (1). The electrons are therefore likely to recombine with atoms to form negative ions (1), which then choke off the discharge completely (1.1). These negative ions further alter the field strength and have to travel sufficiently far away for a new discharge to commence (1.1). The negative ions might also serve as a source for new initiatory electrons.
Figure 4.12: Physical processes during the decay phase of a type 1 Trichel pulse (1), (1.1) and a type 2 Trichel pulse (2), (2.2). Electrons, atoms, positive ions and negative ions are represented by a blue dot, an unfilled circle, a filled circle (red) and a circle with a blue dot, respectively.

The type 2 Trichel pulses are not governed by secondary emission or the secondary emission gets choked off very fast by negative ions (2). The attachment region might therefore be closer to the cathode than for a type 1 Trichel pulse (2). The consequence is that the negative ions have to travel a longer distance until the electric field is restored (2.1). The longer clearing time results in the lower observed discharge frequency. Additionally, a smaller amount of negative ions might be present in the entire gap. The availability of new starting electrons due detachment from negative ions might therefore be reduced.

Coming back to the initial observation of an intermittent discharge behaviour it is of interest if this discharge behaviour is caused or at least partly associated with the occurrence of type 2 Trichel pulses. To investigate this the discharge current pulse amplitudes, $\hat{I}_{TO}$, of a 200 ms discharge current time series are
divided into type 1 and type 2 Trichel pulses\textsuperscript{17}. Their time of occurrence is then, as for a PRPD-diagram, related to the period of the fundamental frequency of the applied voltage i.e. 20 ms at 50 Hz. The ten 20 ms time frames are afterwards plotted into one diagram. The result is shown in Figure 4.13. It is evident that both pulse types show a voltage dependency. Therefore, it is not the pulse type in general that is responsible for the loss of the voltage sensitivity. It is however important to note that the voltage level dependency seems to be clearer for type 2 Trichel pulses. This could be caused by the lower amount of ions in the gap and the lower availability of starting electrons. A new discharge can then ignite into a gap with reduced space charge influence. The pulse amplitude and duration are then mainly governed by the initial field stress i.e. the ignition voltage.

![Figure 4.13: Pulse amplitude of the current through the test object, $\hat{I}_{TO}$, and voltage, $V$, as a function of time, $t$, recorded at -21.5 kV. Type 1 Trichel pulses are given in a) and Type 2 Trichel pulses in b).](image)

Furthermore, it could be observed that the discharge frequency is higher if type 1 Trichel pulses are solely active as compared to a combined type 1 and type 2 activity. Similar observations have been made by Amin \cite{122}. He reported a higher discharge frequency for type 1 Trichel pulses (unconditioned) than for type 2 Trichel pulses (conditioned). Two time series of the discharge current that illustrate this behaviour are depicted in Figure 4.14. In a) only type 1 Trichel pulses are active and in b) both, type 1 and type 2 Trichel pulses are active. It is

\textsuperscript{17}The pulse types have been differentiated based on their fall times. Pulses with a fall time below 1 µs have been counted as type 2 pulses and above as type 1 pulses.
furthermore evident from Figure 4.14 a) that the solely activity of type 1 Trichel pulses in combination with the high repetition rate seems to be the cause for the voltage level insensitivity. A possible explanation for this could be as follows: At high discharge frequencies and primarily type 1 Trichel pulse activity the negative ions, even though being sufficiently far away for the ignition of a new discharge, might still be close to the cathode. The negative ions then keep the ionisation region narrow and provide a source of new starting electrons. If the ionisation region is narrow, then the buildup of a positive space charge is also very close to the cathode. This results in a fast quenching of the impact ionisation and hence a smaller discharge current amplitude. The resulting discharge magnitude is then primarily governed by the buildup and removal rate of the negative space charges and is not driven by the externally applied field strength. Consequently, the discharge magnitude does not follow the instantaneous value of the applied voltage and a $Q(\varphi)$-diagram appears as a flat band as is shown in Figure 4.9 b). It is possible that at a much higher ripple e.g. 5 % the formerly described effect plays a minor role due to the larger variation of the externally applied field.

![Figure 4.14: Current through the test object, $I_{TO}$, and voltage, $V$, as a function of time, $t$, recorded at -22.6 kV. In a) only type 1 Trichel pulses are active and in b) both type 1 and type 2 pulses are present.](image)

Up to this point the intermittent behaviour has been treated as separately occurring from a time dependent position. However, if a longer recording of discharge activity is performed, it is likely that both patterns appear individually or are blurred into one pattern. An exemplary $Q(\varphi)$-diagram is shown in Figure
Two bands of discharges are visible. The first shows voltage sensitive discharge magnitudes between 500 pC and 1000 pC, whereas the second appears as a flat band at about 200 pC. A recording of the discharge current, as per Figure 4.15 b) and c), reveals the physical nature of the pattern formation. It can be seen that a large pulse (leading) is followed by a second pulse that has an amplitude of about one-third of the previous pulse. After a duration of no discharge activity the process repeats. The discharge current amplitudes, \( I_{TO} \), of the pulses are therefore in good agreement with the observed discharge magnitudes, \( Q \). It implies that the discharge magnitudes in the range of 200 pC are caused by the small pulses and that the large, leading pulses result in the voltage sensitive discharge distribution. At higher voltage levels the number of consecutive pulses increases. This scheme is in general similar to the well-known "primary-secondary-streamer" arithmetic of positive corona, which will be analysed in detail in Section 4.2.

![Figure 4.15: Discharge magnitude, Q, and ripple voltage, \( \Delta V_{DC} \), as a function of the phase angle, \( \varphi \), recorded at -25.9 kV a). Current through the test object, \( I_{TO} \), and voltage, \( V \), as a function of time, \( t \), b), as well as a magnified version of the current c).](image)

Again, type 1 and type 2 Trichel pulses are active in the aforementioned discharge series as is shown in Figure 4.16\(^\text{18}\). The following generic observation could be made. The leading pulse can either be of Trichel type 1 or type 2. If a type 2 pulse occurs then the following pulse is likely to appear faster than if the lead pulse was a type 1 pulse.

\[ \text{18The lead pulse amplitude is at 3.5 mA. The lead pulse is not completely displayed to give a better resolution of the consecutive pulses and the decay phase of the lead pulse.} \]
Figure 4.16: Current through the test object, $I_{TO}$, as a function of time, $t$, illustrating the time dependencies between a leading pulse and its successors. The leading pulse is of Trichel type 1, a), and type 2, b).

If the voltage is further increased another pattern can be observed as is depicted in Figure 4.17 a). The lowest discharge magnitude occurs in the maximum of the voltage, whereas the highest discharge magnitude occurs in the minimum of the voltage. The pattern is therefore anti-proportional to the voltage. A corresponding 20 ms time series of the current measured in series with the test object is shown in part b) of Figure 4.17. The magnified version of the latter, which is depicted in part c) emphasizes the physical nature of the observed pattern. The pulse amplitudes, show a voltage level dependence. The amplitude is larger in the voltages minimum then in the maximum. Additionally, only type 1 Trichel pulses could be observed as is indicated in Figure 4.17 d). It is therefore likely that due to the higher field strength in the maximum of the voltage and the corresponding increased ion mobility the positive ions become more effective in choking of the electron multiplication via impact ionization. This leads to lower pulse amplitudes. In the minimum of the voltage where the field strength is lower the ion mobility is lower and consequently larger pulse amplitudes are observed.
A further increase of the voltage leads to the next stage of negative corona, which is the glow discharge. It develops out of the falling flank of a Trichel pulse as shown in Figure 4.18 b) and c). At this point the field is so efficient in removing negative space charges that the secondary emission is not choked off by the negative ions. Consequently, the discharge is now governed by the Townsend mechanism. If the field strength is reduced due to a lower voltage then the negative ions can choke off the secondary emission and regular type 1 Trichel pulses are to be observed as is shown in Figure 4.18 d). The glow discharge itself cannot be detected with the apparent charge method. Therefore, discharge magnitudes are only recorded between approximately 230° and 290° in Figure 4.18 a).

Figure 4.18: Discharge magnitude, $Q$, and ripple voltage, $\Delta V_{\text{DC}}$, as a function of the phase angle, $\varphi$, recorded at -36.4 kV, a). Current through the test object, $I_{\text{TO}}$, and voltage, $V$, as a function of time, $t$, b), as well as a magnified version of the current c) and d).
Figure 4.19 a) indicates that no pattern can be detected if the glow discharge is reached throughout the whole voltage range of the ripple. A larger ripple might therefore be favourable as the voltage span until the glow state is reached will be larger. The continuous current that is flowing in the glow regime is proportional to the voltage as shown in Figure 4.19 b). This fact offers an option for an improved detection system that is able to properly represent direct current components as an additional information in the PRPD representation.

The basic idea behind this improved detection system is to add an additional MPD 600 measuring device\(^\text{19}\) into the test circuit. This measuring device is used solely for a voltage measurement across an additional series resistor in front of the test object. The measured voltage is then proportional to the continuous current of the glow discharge. The glow regime can then easily be identified. An example of a corresponding recording is given in Figure 4.20\(^\text{20}\). It can be seen that the voltage, which is proportional to the negative discharge current through the test object clearly increases with enhanced voltage. Hence, an identification of glow discharge activity is easily possible.

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\(^{19}\)In general any oscilloscope or transient recorder that is able to accurately resolve a signal that has voltage components identical to those of a half-wave rectification can be used.

\(^{20}\)The examination has been performed at a ripple of 4.5 % to indicate the general applicability.
Figure 4.20: Discharge magnitude, \( Q \), and ripple voltage, \( \Delta V_{DC} \), as a function of the phase angle, \( \varphi \), recorded at \(-38.5 \) kV, a) and \(-41.7 \) kV b). The ripple is 4.5 \%.

At an even higher voltage, negative streamers are developing out of the glow discharge. A corresponding pattern is given in Figure 4.21 a). The pattern is composed of three concentrations of discharges, where the lower two, in terms of discharge magnitude, are about five to ten times smaller than the larger one. To form such a pattern three different discharge pulses by means of amplitude and / or pulse duration characteristics have to be active. An analysis of the discharge current, which is exemplarily shown in Figure 4.21 b) and c) did not reveal a pulse behaviour that fits the aforementioned pattern.

Figure 4.21: Discharge magnitude, \( Q \), and ripple voltage, \( \Delta V_{DC} \), as a function of the phase angle, \( \varphi \) a), recorded at \(-47.1 \) kV. Current through the test object, \( I_{TO} \), and applied voltage, \( V \), as a function of time, \( t \), b), as well as a magnified version of the current c).

Another approach to determine the physical background of the three level pattern is made by examining the dependencies of times between discharges and the related discharge magnitude differences. Figure 4.22 reveals several tendencies. However, only three possible scenarios can be clearly taken from this figure. A
large pulse can follow a small pulse i.e. $Q_{i+1} > Q_i$, indicated by black dots, and $dQ > 300$ pC. The time interspacing between them ranges from approximately 100 $\mu$s to several hundred milliseconds. A small pulse can follow a large pulse i.e. $Q_{i+1} < Q_i$, indicated by red dots, and $dQ > 300$ pC. The corresponding time interspacing is below 120 $\mu$s. Furthermore, a small pulse can follow a small pulse i.e. $Q_{i+1} < Q_i$, indicated by red dots, and $dQ < 20$ pC. The time interspacing is below 100 $\mu$s.

Figure 4.22: Magnitude difference between two consecutive discharges, $dQ$, as a function of time between these discharges, $dT$.

An examination of the discharge current should consequently show small pulses up to 120 $\mu$s after a streamer discharge (large pulse). This is not the case as is exemplary shown in Figure 4.23 a) and b). However, a precise examination of the former Figures, gives rise to a possible explanation. The pulse decay phase does, like a Trichel pulse, show a change of the slope of the current. The change of the slope itself seems to be more abrupt as compared to a Trichel pulse. The time between pulse maximum and point of change of the slope is 20 $\mu$s. It hence, falls within the estimated time between large pulse and small pulse. Consequently, it has to be assumed that it is this gradient change that is responsible for the detection of an additional PD event. The small magnitude pattern in Figure 4.21 is therefore very likely a measurement error. Nevertheless, this small magnitude pattern makes the differentiation between negative corona inception, e.g. Figure 4.8 and negative streamer onset easier. A removal of these measurement errors from the negative streamer pattern would make the two patterns look alike.
Even though, it has been argued that at least one of the two lower magnitude patterns from Figure 4.21 a) is caused by a measuring error no explanation for the second pattern has been given so far. To further access the pattern formation the discharge magnitude and time dependencies of the discharges, which are related to those two patterns have been further analysed. Special interest has been put into the separation of successor and predecessor of a discharge. The results are depicted in Figure 4.24, where a) belongs to discharge magnitudes between 35 pC and 70 pC and b) to discharges between 10 pC and 35 pC.

It is evident from a) that a recorded discharge magnitude in the range of 35 pC to 70 pC is always preceded by a discharge of about 400 pC. It can be succeeded by a discharge of about 400 pC or of 10 pC to 35 pC. Discharges in the range of 10 pC to 35 pC are never succeeded by small magnitude discharges. They are always followed by a large magnitude discharge. Again, as has already been mentioned,
the discharge current did not reveal any small discharge pulses in addition to the streamers. Hence, it is the authors' opinion that also the second low discharge magnitude pattern is caused by an integration error of the measurement system. A further enhancement of the voltage leads to enhanced streamer activity that finally results in a breakdown of the gap. No additional pattern could be observed.

In this subsection, six different patterns that are associated with the application of a negative direct voltage containing a ripple have been presented. They are formed due to Trichel pulses, pulseless glow and negative streamers. It can be concluded that a ripple of 0.8 % to 1.1 % is sufficient to have a visible effect throughout the voltage range of negative corona until breakdown occurs.

4.2 Positive corona in air

The point to plane arrangement, which has been examined in Section 4.1 with respect to a negative dc voltage is now stressed with a positive dc voltage. The voltage is again obtained via half-wave rectification of an ac voltage. The measuring devices and the equivalent circuit, except for the direction of the diodes, are also identical. The evaluation procedure is equivalent to the one used in the negative corona case. It is first accessed if the ripple has an influence on the general discharge behaviour. The findings are presented and discussed in Subsection 4.2.1. Based on these results, the different phase resolved partial discharge patterns are evaluated at a fixed value of the ripple. Subsection 4.2.2 discusses the corresponding investigation.

4.2.1 Influence of the ripple on the discharge behaviour

As for the negative corona case, the influence of the ripple on the discharge behaviour is investigated by varying the ripple at a constant peak value of the applied voltage and recording the resulting discharge current time series. To evaluate the influence of the ripple, the discharge frequency, $f_d$, the average pulse amplitude, $\tilde{I}_p$, the average pulse rise time, $\bar{t}_{rt}$, and the average pulse fall time, $\bar{t}_{ft}$, have been obtained from the discharge current time series by means of the methods described in Subsection 3.3.1. Recordings have been made at two different voltage levels. In contrast to the negatively stressed point, the selection of the voltage levels under observation is different. In general, the onset voltages of pos-
itive and negative corona are approximately similar but the breakdown voltage of positive corona is much lower [134]. Consequently, the voltage range of the occurring discharge phenomena of positive corona is more dense. Therefore, it is not feasible to place two voltage levels, in the short band of one discharge form. Even more important is the fact that in the negative corona case one of the two mainly active discharge mechanisms, the pulseless glow, is in-evaluable by means of the wideband apparent charge method as has been argued in Subsection 4.1.1. For the positive glow corona this is not the case as this discharge phenomenon is characterised by a regular pulsation, which has for example been shown by [75]. It can thus be detected by means of the apparent charge method e.g. [133]. One evaluation level is hence settled at 24 kV, which is in the streamer / burst pulse region, whereas a second level has been placed in the glow region at 26 kV. To evaluate the discharge frequency it has been decided to only use streamer discharges as they occur in the streamer-burst-pulse region as well as in the glow regime. Their pulse properties make an evaluation easier when compared to burst pulses. Results for the discharge frequency as a function of the voltage ripple at the 24 kV level have already been published in a paper by the author [121]. The other parameters were not evaluated in this publication and no detailed explanation for the underlying physical effects were given.

The measurements were carried out at a temperature of 23.1 °C, a relative humidity of 57.1 % and at a pressure of 1000.8 hPa. All environmental data is given as average values over the whole measurement duration.

The discharge frequency, \( f_d \), as a function of the voltage ripple, \( V_{R\%} \), at 24 kV and 26 kV is illustrated in Figure 4.25. For an amplitude of 24 kV the discharge frequency stays constant up to a ripple of about 2 %, followed by a weak decay up to 5 % and a strong decay above 5 %.
Figure 4.25: Discharge frequency, $f_d$, as a function of the voltage ripple, $V_{R\%}$.

An explanation for the observed behaviour is achieved by comparing the different underlying discharge current time series. This is visualized in Figure 4.26.

Figure 4.26: Voltage, $V$, discharge current, $I_{TO}$, and first derivative of the voltage as a function of time, $t$, at a ripple of 0.4 % a), 3.5 % b), 8.5 % c), 13.5 % d)

When Figure 4.26 a) and Figure 4.26 b) are compared to each other, a slight difference in streamer activity is visible for a ripple of 3.5 %, especially in the
region of the minimum of the applied voltage. This difference is caused by the field strength sensitivity of streamer activity [69], which is related to the voltage. At a ripple of 8.5 % the region where streamers can ignite is limited due to the inception voltage, as is evident from the blank times in Figure 4.26 c). This leads to a reduction of the discharge frequency. Additionally, a slight divergence in inception and extinction voltage is visible at a ripple of 8.5 %, as well as a new mechanism that leads to primary and secondary\textsuperscript{21} streamers. To further illustrate the reported behaviour a magnified version of the current through the test object, $I_{TO}$, is depicted in Figure 4.27 a).

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure4_27.png}
\caption{Current through the test object, $I_{TO}$, and voltage, $V$, as a function of time, $t$, with respect to the streamer regime a) and to the burst regime b).}
\end{figure}

Liu et al. [136] have reported a similar primary-secondary streamer relation for positive corona discharges from a conductor. In their study the authors argued that the ignition of the primary pulse is determined by a Laplacian i.e. space charge free field, which leads to the higher pulse amplitude. They also reported that the secondary pulses are almost independent of the voltage, which is supported by the findings of this thesis as is shown in Figure 4.27 a). However, the assumption of a completely space charge free field contradicts the observed burst pulse activity, which precedes the primary\textsuperscript{22} streamer as can for example

\begin{footnotesize}
\begin{itemize}
\item[21]Secondary streamer is a semi optimal term, as this term is usually used in context of complete breakdown processes e.g. [135].
\item[22]It is not possible to access whether burst pulses are active between primary and secondary streamers due to resolution limitations of the measuring system.
\end{itemize}
\end{footnotesize}
be seen in Figure 4.27 b) at about 7.2 ms. It is not possible to argue, whether the different test geometries or the measurement devices$^{23}$ used are responsible for the different observations. Nevertheless, as burst pulses spread radially across the point surface and are of much smaller magnitude, the distribution of space charges throughout the gap might be less dense then after a streamer. It is therefore, still plausible to argue that the positive ions of the primary streamer are responsible for the lower magnitudes of the secondary streamers.

It can be argued that Figure 4.26 d) shows that at a ripple of 13.5 % the formerly described primary-secondary streamer mechanism becomes persistent. However, the time domain inter spacings of the occurring streamer discharges indicate that this is not the case. In general streamer discharges showed a time separation of about 500 $\mu$s, irrespective of the ripple. The separation of a primary and a secondary streamer at a ripple of 8.5 % was between 100 $\mu$s and 150 $\mu$s, whereas at a ripple of 13.5 % it took 500 $\mu$s to 2500 $\mu$s between a large streamer and its successor and about 500 $\mu$s between the following streamers. Hence, usual streamer separation and a new streamer separation can be observed. No primary-secondary streamer separation is active. Additionally, no burst pulses were observed prior to one of the large streamers but were active afterwards as is illustrated in Figure 4.29. The large streamers did only appear at the rising flank of the applied voltage and showed a tendency to ignite well above the onset voltage. The different time dependencies have been put together in Figure 4.28.

$^{23}$Burst pulses are about a thousand times smaller than streamer discharges and are therefore easily overlooked.
Hereinafter, an attempt is made on a physical explanation for this newly occurring phenomenon. It can be assumed that these large streamer pulses start in a space charge free field due to the absence of burst pulses before the ignition of such a large streamer. Two facts that are associated with this space charge free field might contribute to the large pulse amplitude. Firstly, the pulse can propagate unhindered into the gap. Moore and English have related an increased streamer length to the absence of positive ions in their study on point to plane corona due to impulse voltages [137]. Secondly, due to the absence of ions one source of starting electrons is missing. Therefore, the statistical time lag between potential onset and actual onset increases. This leads to a higher ignition voltage due to the waveform of the voltage. The higher voltage is associated with a higher field strength, which in turn results in a higher ionization. The consequence is a larger pulse amplitude.

Figure 4.29 b) indicates that the time frame between the first streamer and its successor is completely occupied by burst pulse activity. This comparatively long burst pulse activity might be the reason for the increased time between the first streamer and its successor. The increased burst duration could be caused by two interacting mechanisms. Firstly, it is plausible to assume that the larger the pulse amplitude the more particles are traversing through the gap. Therefore, a longer clearing time might be required until the next streamer discharge can
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The increased amount of particles, especially the positive ions, will favour burst pulse activity in the vicinity of the point electrode.

The second mechanism is attributed to the ripple and therefore to the ac components of the voltage. Those ac components cause a displacement current, which is superimposed on the conduction current as can be seen in Figure 4.29 b) from 4.0 ms to 5.8 ms. This current component influences the surface charge of the electrodes and the resulting electric field. For a positive current in the external circuit electrons are taken from the point electrode, which increases the points positive potential. As the voltage regions of the different positive corona mechanisms are narrow, the increased potential might be high enough to transform the burst pulses into a pulsating glow corona. This glow corona is in turn responsible for the elongated time between consecutive streamers.

Figure 4.29: Current through the test object, $I_{TO}$, and voltage, $V$, as a function of time, $t$, with respect to the streamer regime a) and to the burst regime b).

At 26 kV the discharge frequency behaviour is ambiguous, as is shown in Figure 4.25. At first the discharge frequency increases with increasing ripple, then stays almost constant up to 10 % and finally decreases in the same manner as for 24 kV. The three different behavioural sectors can be explained as follows: The strong increase between 0 % and 0.6 % is caused by the glow inception voltage. At the lowest possible ripple it can be assumed that the glow inception is reached throughout the complete period of the applied voltage. The higher the ripple becomes the more time instances exist where the applied voltage is below the
glow inception voltage and therefore, resides in the streamer-burst pulses regime. At ripple values between 0.6 % and 10 % streamer and burst activity are the dominant discharge mechanisms with respect to one period of the applied voltage. The decay in discharge frequency for ripple values larger than 10 % takes place as the voltage does not only leave the glow regime but also falls below the corona onset. Furthermore, it can be argued that the discharge behaviour shows the tendency to be intermittent between the streamer / burst pulse (0 to 120 ms) and the glow region (above 120 ms) at the selected amplitude of 26 kV, as is shown in Figure 4.30. This makes the derivation of a general expression questionable. Therefore, it has been decided to leave out the glow regime from the conclusion on the maximum tolerable ripple.

![Figure 4.30: Current through the test object, $I_{TO}$, and applied voltage, $V$, as a function of time, $t$, recorded at an amplitude of 26 kV at 0.6 % ripple.](image)

Nevertheless, the foregoing considerations lead to the following conclusion with regard to the influence of the ripple on the discharge frequency for positive corona in the streamer / burst pulse regime: The ripple has no significant influence up to 2 %. Above 2 % a reduced discharge activity due to the variation of the voltage with time occurs. Starting between\footnote{A precise value cannot be given, due to the unavailability of resistor capacitor combinations to produce intermediate ripple values.} 8.5 % and 13.5 % a new scheme that involves a large streamer that is followed by a short period of positive glow which is succeeded by normal streamer / burst pulse behaviour can be observed.
This new scheme is caused by the increasing displacement current. It is therefore recommended to conduct positive corona partial discharge tests at dc voltages containing less than 2 % ripple.

The average pulse amplitude, $I_p$, as a function of the ripple is depicted in Figure 4.31.

![Figure 4.31: Average pulse amplitude, $I_p$, as a function of the voltage ripple, $V_{R\%}$.

For a peak value of the voltage of 24 kV the average pulse amplitude stays constant up to a ripple of 2 %. It is then followed by a weak decrease with increasing ripple until approximately 10 %. A further enhancement of the ripple results in a larger average pulse amplitude, which is accompanied by a vast increase in its standard deviation. At 26 kV the same tendencies can be observed. The previously described behaviour can be explained in the same manner as the discharge frequency. At first the average pulse amplitude decreases due to the voltage level sensitivity of the streamer amplitude. The increased pulse amplitude might be caused by the newly observed occurrence of large streamers at higher ripple values. Support to this hypothesis is given by the aforementioned strongly increased standard deviation.

An examination of the average pulse rise time and average pulse fall time, as per Figure 4.32 and Figure 4.33, does not reveal any new behaviour and further supports the requirement for positive corona tests to be carried out at a ripple smaller than 10 % to maintain the general pulse properties.
Figure 4.32: Average pulse rise time, $\bar{t}_{rt}$, as a function of the voltage ripple, $V_{R\%}$.

Figure 4.33: Average pulse fall time, $\bar{t}_{ft}$, as a function of the voltage ripple, $V_{R\%}$.

The previously presented examination of the four selected characteristic discharge pulse parameters show again that the main limiting factor in terms of tolerable ripple is the discharge frequency. This leads to the conclusion that positive corona tests must be carried out at a ripple below 2 % to have a dc like discharge behaviour by means of discharge frequency and discharge pulse attributes.

### 4.2.2 Influence of the voltage on the discharge behaviour

In Subsection 2.2.2 it was pointed out that the appearance of positive corona in air does change with the value of the applied voltage. This holds true if an alternating
voltage is applied [66], [138] and if a pure dc voltage is applied. In [133] the author has shown that for positive dc voltages that contain a ripple burst pulses, positive streamers, pulsating glow and breakdown streamers can be observed. A ripple of 5.5 % was used to evaluate the corresponding phase resolved patterns. This ripple is above the 2 % recommendation that was suggested in this work. Additionally, in [121] by the author, characteristic patterns for the streamer / burst pulse region have been derived for a ripple of 0.9 %. Other discharge phenomena of positive corona have not been treated at this ripple. Hence, the patterns are re-evaluated at a ripple of 0.9 %. This ripple has been selected on the basis of pretests, which showed that below this ripple the visual pattern recognizability is not doubtless throughout the complete spectrum of positive corona discharge phenomena. This holds especially true above the corona onset. The tests have been carried out at a temperature of 19.4 °C, a relative humidity of 38 % and at an air pressure of 983.0 hPA. All environmental data is given as average values over the whole measurement duration.

The first pattern that can be observed is shown in Figure 4.34 a). The discharges that occur at positive corona onset are of small magnitude, which is sensitive to the voltage. The recorded discharges seem to be grouped at specific phase angle instances, which shall be further examined.

![Figure 4.34: Discharge magnitude, Q, and ripple voltage, ∆VDC, as a function of the phase angle, ϕ, a). Current through the test object, I_TO, and voltage, V, as a function of time, t, recorded at 19.0 kV b), as well as a magnified version of the current c).](image)

An analysis of the current measured in series with the test object, as is shown in Figure 4.34 c), reveals the physical nature of the discharge magnitude grouping. The discharges appear in groups that are composed of an initial pulse that
Is followed by several smaller pulses. Such pulse series have for example been reported by Amin [70] as well as Miyoshi and Hosokawa [139]. The pulses are referred to as burst pulses or burst corona. Their cause of formation is described in Subsection 2.2.2. A time resolved representation of the discharge magnitudes, $Q$, of the pulses depicted in Figure 4.34 c) has been given in Figure 4.35. It can be seen that the time difference between the three occurring pulses, as well as their amplitude difference is properly represented in the resulting discharge magnitudes. A plot of these discharge magnitudes into a $Q(\varphi)$ diagram results in the three red points in Figure 4.34 a), which are grouped at a phase angle of approximately 155°.

![Figure 4.35: Discharge magnitude, $Q$, as a function of time, $t$.](image)

If the voltage is further enhanced additional pulses of a much higher magnitude\textsuperscript{25} appear in the vicinity of the maximum of the voltage as is shown in Figure 4.36 a). The previously mentioned burst pulses are still active at phase angles that correspond to a lower voltage e.g. above 180°.

\textsuperscript{25}The discharge magnitude scaling of the recorded large pulses is a bit misleading in so far as the three depicted pulses show an identical magnitude. This identical magnitude was measured because of an overflow of the input channel of the measuring device. This overflow does have an influence on the magnitude, in form of a cut off, but does not alter the general discharge occurrence. Nevertheless, it has been decided to show this diagram to illustrate that large pulses and small pulses can appear independently.
Figure 4.36: Discharge magnitude, $Q$, and ripple voltage, $\Delta V_{DC}$, as a function of the phase angle, $\varphi$ recorded at 19.1 kV a) and 20.0 kV b)

Figure 4.36 b), indicates that large pulses and burst pulses can also coincide. A recording of the discharge current, depicted in Figure 4.37, supports this as large pulses are directly followed by burst pulses. The large pulses are referred to as onset streamers. Their physical mechanism has been given in Section 2.2.2. If streamers are followed by burst pulses then the burst pulses are a direct consequence of the positive space charge that builds up in the vicinity of the anode due to a previous streamer discharge [20].

Figure 4.37: Current through the test object, $I_{TO}$, and voltage, $V$, as a function of time, $t$, recorded at 20.0 kV, as well as a magnified version of the current. Focus on streamer discharges a) and b) and focus on burst pulses c) and d).

The first part of this subsection can be concluded by stating that at positive corona onset three different patterns can be identified. These are characterized by:
• Groups of small discharge magnitude pulses that show a tendency to align in a linearly decaying way.

• Large discharge magnitude pulses in the vicinity of the maximum of the applied voltage and small discharge magnitude pulses throughout the rest of the voltage cycle.

• One large discharge magnitude pulse that belongs, as seen from a viewpoint of the phase angle, to a group of small magnitude pulses.

These patterns correspond to burst pulses, independent streamer and burst pulses as well as dependent streamer and burst pulses, respectively.

Dependent streamer and burst pulses occur rather sporadic at positive corona onset, whereas at slightly higher voltages they become more frequent. A corresponding $Q(\varphi)$-diagram is shown in Figure 4.38 a). The discharge magnitudes appear in two bands, which at a first glimpse do not show any specific relation that might serve for distinguishing purposes. However, if the scaling is adjusted to properly display the high magnitude region of streamer activity, as is shown in Figure 4.38 b), the voltage sensitivity becomes visible, which can hence be used as an identifying attribute.

Figure 4.38: Discharge magnitude, $Q$, and ripple voltage, $\Delta V_{DC}$, as a function of the phase angle, $\varphi$, recorded at 20.5 kV a), as well as a magnified version of the streamer region b).

A magnitude dependence of the burst pulses towards the voltage could not be observed as is indicated in Figure 4.39 a). If the $Q(\varphi)$-diagram is modified by introducing a third discharge quantity a pattern becomes visible as is shown in Figure 4.39 b). This third attribute is literally a quantity. It represents the number of discharges that occurred with respect to a certain phase angle range.
In the presented graph the phase angle has been subdivided into 36 clusters. Each cluster spans over 10 degrees and contains the corresponding discharge magnitudes. Based on the number of discharges per cluster the point size of each individual discharge has been set. The result is that areas with large points represent a higher discharge activity than areas with small points. Therefore, it can be concluded that the burst pulse activity is higher in the vicinity of the maximum of the voltage than around the minimum of the voltage.

Figure 4.39: Discharge magnitude, \( Q \), and ripple voltage, \( \Delta V_{DC} \), as a function of the phase angle, \( \varphi \) recorded at 20.5 kV a) as well as an advanced version b) (description in the text).

Increasing the voltage even further leads to an increase in the discharge magnitude that is accompanied by a reduction of streamer discharge activity as is indicated in Figure 4.40. The number of streamer discharges, which have been recorded during a 120 s time frame, are 55172 at 21 kV and 5657 at 23.9 kV. They are shown in Figure 4.40 a) and b), respectively.

Figure 4.40: Discharge magnitude, \( Q \), and voltage, \( V \), as a function of the phase angle, \( \varphi \), recorded at 21 kV a) and 23.9 kV b).

The aforementioned behaviour is also recognizable at the discharge current
measured in series with the test object. In Figure 4.41, five, 20 ms periods of the discharge current are shown at 21.0 kV, part a), and 23.9 kV part b). The reduction of streamer activity with increasing voltage is clearly visible. It is also noteworthy that the time between streamer discharges is completely filled with burst pulses\textsuperscript{26}. This observation allows a physical explanation of the reduction in the streamer activity. A higher discharge current amplitude can be related to an increased amount of charge moving through the gap, to an enhanced movement speed of the latter or both. It is likely that both mechanisms are involved at the higher discharge current amplitude, as the higher field stress does on one hand enhance the ionisation coefficient and on the other hand increase the particle movement speed. This will result in a larger amount of positive space charge in the vicinity of the anode that, due to the sheer amount, suppresses streamer activity and due to the increased clearing speed favours burst pulses.

Figure 4.41: Current through the test object, $I_{TO}$, and voltage, $V$, as a function of time, $t$, recorded at 21.0 kV a) and 23.9 kV b).

With respect to the burst pulses it can be reported that above 21 kV no relation between discharge magnitude, including the number of discharges, and the level of the voltage can be found. It is likely that the reduction in streamer activity in combination with the continuing burst pulses marks the beginning transition into the pulsating glow regime. From the point of the discharge current it is not possible to state a precise voltage level at which the pulsating glow discharge is

\textsuperscript{26}This is not shown, as no proper resolution can be achieved due to the high burst pulse repetition rate in comparison with the time between streamer pulses.
the dominant discharge mechanism as no prominent waveform change does occur. It has therefore been decided to introduce a transition definition. The definition is as follows: If no streamer discharges appear during one period of the dominant voltage harmonic while burst pulses are continuously active then the discharge is a pulsating glow discharge. This definition is limited to total harmonic contents which are below 2 %.

If the voltage is further enhanced the pulsating glow regime, based on the former definition, is reached. A corresponding time series of the current measured in series with the test object is given in Figure 4.42. The absence of streamer discharges and the continuing activity of burst pulses over the span of more than one period is clearly visible.

Figure 4.42: Current through the test object, $I_{TO}$, and voltage, $V$, as a function of time, $t$, recorded at 25.2 kV. Focus on streamer discharges a) and focus on burst pulses / pulsating glow b).

At even higher voltages streamer discharges disappear completely. Two corresponding $Q(\varphi)$ diagrams are shown in Figure 4.43. One has been recorded at 26.1 kV, whereas the other one has been recorded at 27.8 kV. It is not possible to distinguish the two graphs from one another based on the discharge magnitude. Also an evaluation of the number of discharges did not enable distinguish-ability.

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27 Originally, it was termed Hermstein glow after the author who first reported on this discharge mechanism [73]. However, during this time it was believed that it is a pulseless discharge type, which was disproved later on e.g. [75].
4 Corona in air

Figure 4.43: Discharge magnitude, $Q$, and ripple voltage, $\Delta V_{DC}$, as a function of the phase angle, $\varphi$ recorded at 26.1 kV a) and 27.8 kV b).

However, a recording of the underlying discharge currents as is shown in Figure 4.44 reveals a feature that might lead to a differentiation. It can be seen that the two time series show different dc current components. Therefore, the discharge magnitudes should be larger for 27.8 kV when compared to 26.1 kV.

![Figure 4.44: Current through the test object, $I_{TO}$, and voltage, $V$, as a function of time, $t$, recorded at 26.1 kV a) and 27.8 kV b).](image)

Additionally, the discharge magnitudes should show a dependency upon the voltage and therefore, follow the waveform of this voltage, which would result in an identifiable pattern. This is obviously not the case and hence the dc component must be cut off. This cut-off is caused by the measuring principle of the apparent charge method, which relies on the charge delivered by a coupling capacitor. For dc components this capacitor acts as an open circuit (steady state assumed). Therefore, no further pulsating glow discharge identification is possible by means
of the apparent charge method. The foregoing considerations imply the need for an advanced measuring system that is capable of providing information on the dc component of the discharge current. It is suggested to use a measuring system equivalent to the one proposed in Subsection 4.1.2.

No breakdown streamers could be observed at the environmental conditions. Therefore a qualitative explanation of the pattern shall be given based on [133]. The pattern itself is nearly identical with the onset streamer pattern shown in Figure 4.36 a) except that continuous pulsating glow activity results in a band of discharges in the low pC range. The breakdown streamers have been reported to occur very sporadic with time separations running up to minutes. Hence, for positive corona five different patterns can be reported. They are formed due to burst pulses, streamers, a combination of the former, pulsating glow discharges and breakdown streamers.

4.3 Summary

In this chapter the behaviour of a point to plane arrangement has been analysed with respect to a dc voltage that contains a ripple due to a half-wave rectification of an ac voltage. The influence of the ripple on the discharge behaviour has been examined as well as characteristic phase resolved patterns have been derived. The main findings are as follows:

For negative corona it has been shown that the discharge frequency of Trichel pulses decreases with increasing ripple. This decrease has been attributed towards a reduced movement of negative ions and an altered electric field due to a displacement current. The discharge frequency shows a dc like behaviour for a ripple below 3 %. The average pulse amplitude, the average pulse rise time and the average pulse fall time strongly deviate from the dc behaviour at ripples that are bigger than 10 %. It is therefore recommended to conduct dc PD tests with a ripple below 3 %. Based on this recommendation phase resolved partial discharge tests have been conducted. Six different patterns have been observed, which can be used to clearly identify negative corona discharges with a ripple between 0.8 % and 1.1 %. The first pattern is formed due to Trichel pulses at negative corona onset. The second pattern is a spread of the former pattern throughout the complete phase angle range. The discharge magnitudes
contained in both patterns are sensitive toward the level of the voltage at which the discharges ignited. The third pattern is also formed by Trichel pulses. In this pattern the discharge magnitudes are however not sensitive towards the voltage. It has been shown that this pattern can be observed, when type 1 Trichel pulses are active at a high repetition rate. Additionally, the second and the third pattern can be observed simultaneously. The discharge magnitudes in the fourth pattern are anti proportional to the voltage. The pattern appears as an inverted version of the second pattern. The fifth pattern is characterized by the disappearance of discharges starting from the maximum of the voltage. This pattern corresponds to the onset of the pulseless glow regime. As this type of discharge cannot be detected by means of the apparent charge method no pattern can be recorded if the glow regime is reached throughout the complete phase angle range. It could however be shown that a modified detection system is able to properly detect the glow discharge regime. The sixth and last pattern is attributed towards the onset of negative streamers.

The tests conducted with positive corona have shown that the discharge frequency of streamers decreases with increasing ripple. As in the case of Trichel pulses this decrease has been attributed towards the increasing displacement current. Based on the examination of four characteristic quantities it has been shown that positive corona tests should be carried out with a ripple below 2 %. Five different patterns have been observed, which can be used to identify positive corona discharges with a ripple of 0.9 %. The first pattern is formed due to burst pulse activity. It is characterized by groups of discharges in the small pC range, which are sensitive to the voltage. The second pattern that can be observed is due to independent activity of streamers and burst pulses. The third pattern is composed of streamers and burst pulses, which are dependent upon each other. The streamers in general show much larger discharge magnitudes than the burst pulses and are in the nC range. Their discharge magnitude is strongly correlated with the ignition voltage. Hence, higher discharge magnitudes align with the maximum of the voltage. The fourth pattern is characterized by a disappearance of streamers and a transformation of the burst pulse activity into the pulsating glow discharge. As the pulsating glow discharge is basically a never ending burst pulse, which consequently shows an identical waveform of the discharge current no clear border between the two mechanisms exists. For dc voltages with a ripple
below 2 % pulsating glow has been defined as burst pulse activity that spans over at least one full period of the fundamental frequency of the rectified ac voltage without streamer activity. The fifth and last pattern is formed due to the appearance of breakdown streamers out of the pulsating glow regime. In the next chapter the behaviour of a surface discharge arrangement with respect to the proposed method is analysed.
5 Surface discharges in air

In this chapter the behaviour of a test arrangement, as per Figure 3.8, which enforces surface discharges is analysed with respect to the application of a partially rectified voltage. The examination is subdivided according to the polarity of the voltage. Section 5.1 investigates the application of a negative voltage, whereas Section 5.2 looks at the positive voltage. The structure of both sections is identical: Firstly, the test object is stressed with a constant peak value of the dc voltage, while the ripple is varied. These tests are performed to evaluate the ripples influence on the discharge behaviour. The corresponding procedure, results and discussion are given in Subsection 5.1.1 for negative polarity and in Subsection 5.2.1 for positive polarity. Secondly, the same test arrangement is stressed at a fixed ripple and characteristic phase resolved partial discharge patterns for negative and positive surface discharges are obtained. The patterns and their physical cause of formation are explained in Subsections 5.1.2 and 5.2.2.

5.1 Surface discharges at negative voltage polarity

A test arrangement as shown in Figure 3.8 has been stressed with a negative dc voltage that contains a ripple due to a half-wave rectification of an ac voltage. The dielectric barrier used is a laminated paper of type PF CP 201. It is of quadratic shape, with a length of 70 mm. Its thickness is 0.5 mm and the dielectric constant is 5.

5.1.1 Influence of the voltage ripple on the discharge behaviour

The influence of the voltage ripple on the discharge behaviour has been assessed by examining the evolution of four characteristic discharge parameters. These are the discharge frequency, \( f_d \), the average pulse amplitude, \( \bar{i}_p \), the average
pulse rise time, $t_{rt}$, and the average pulse fall time, $t_{ft}$. To study the ripples influence on these parameters the test object has been stressed with a constant peak value of the voltage while the ripple was varied. For the behaviour of the discharge frequency with respect to a varying ripple some results have already been published in a paper by the author [121].

In general the appearance of two different kinds of discharges can be reported. Two exemplary pulses are shown in Figure 5.1. The pulses clearly differ in their rise time and fall time. One pulse is characterized by a fast rise time and an oscillatory pulse decay. The other pulse type shows an about five times slower rise time. After the maximum has been reached the discharge current stays nearly constant for some time before the decay phase commences. Due to the fast rise time it has been decided to name the first pulse, as in the case for internal PD, a streamer-like discharge. The second pulse is referred to as a Townsend-like discharge.

![Figure 5.1: Current through the test object, $I_{TO}$, as a function of time, $t$, for a streamer-like and a Townsend-like discharge.](image)

The different pulse types have been discussed at this point as their properties indicate the requirement for a separate treatment of these pulses with respect to the ripples influence on the discharge behaviour. It is indicated in Figure 5.2 that streamer-like discharges show a much faster rise time than Townsend-

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28 The oscillations have a frequency between 13 MHz and 20 MHz. They are therefore caused by the inductance of the measuring wires, which has been estimated to be between 1.5 $\mu$H and 2.0 $\mu$H and the input capacitance of the GN 110 measuring probe, which is 34 pF.

29 The current is given as absolute values as the built in Matlab function for rise time evaluations...
like discharges. The pulse separation is therefore based on the rise times of the pulses. The border between the pulses has been set to a rise time of 80 ns. For the evaluation of the discharge quantities two voltage levels have been selected. These are -3 kV and -5 kV. The examination has been performed at a temperature of 20.1 °C, a relative humidity of 28.5 % and a pressure of 1006.4 hPa. All environmental data is given as average values over the whole measurement duration.

![Figure 5.2: Current through the test object, $I_{TO}$, as a function of time, $t$, for a streamer-like, a) and a Townsend-like discharge, b). The rise time estimation is indicated.](image)

The discharge frequency, $f_d$, as a function of the ripple, $V_{R\%}$, is illustrated in Figure 5.3. In the case of Townsend-like discharges the discharge frequency stays constant up to a ripple of 0.8 %, irrespective of the voltage. At higher ripple values the discharge frequency decreases for a voltage of -3 kV as well as for -5 kV. Streamer-like discharge activity stays also nearly\(^{30}\) constant up to a ripple of 0.8 %. Afterwards, discharge activity starts to increase with increasing ripple, for a peak value of -3 kV, whereas it stays further constant for -5 kV. The increase of the discharge frequency for -3 kV is superseded by a decrease for ripples bigger than 13.8 %. At a ripple of 8.4 % and a voltage of -5 kV the discharge frequency also shows a decreasing behaviour with increasing ripple.

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\(^{30}\) There is one exception at 0.4 %, which by considering the scatter of the data is treated as an outlier. It is hence not interpreted as being physically caused at this specific ripple.
5 Surface discharges in air

Figure 5.3: Discharge frequency, $f_d$, as a function of the voltage ripple, $V_{R\%}$.
Townsend-like discharges a) and streamer-like discharges b).

At a ripple of 46.1 % and a voltage of -5 kV a remarkable observation can be made. At this point positive discharge pulses start to ignite during the positive part of the rising flank of the voltage. Due to the bipolar pulse activity the discharge frequency has not been evaluated for a ripple of 46.1 % at a voltage of -5 kV. Nevertheless, this newly observed phenomenon shall be further examined. A graphical representation of this phenomenon is shown in Figure 5.4.

Figure 5.4: Current through the test object, $I_{TO}$, as a function of time, $t$, as well as the corresponding voltage, $V$. Recorded at a negative dc voltage with a ripple of 46.1 %.

It can be deduced that the negative discharge magnitudes are higher than

\[^{31}\text{If the dc component is virtually subtracted.}\]

\[^{32}\text{The pulses are cut-off at 22 $\mu$A to achieve a better resolution of the smaller pulses. Larger magnitudes have been evaluated towards their discharge type with a simultaneously recorded time series. This recording has been set to properly represent larger pulse amplitudes at the trade-off of a bad resolution for smaller pulses.}\]
the positive ones. The occurrence of streamer-like and Townsend-like discharges can be reported, irrespective of the discharge polarity.

Similar observations can be made if a positive half-wave rectification is performed as is shown in Figure 5.5. At a peak value of 5 kV and a ripple of 46.0 %, discharge activity takes places in the negative part of the falling flank, as well as in the positive part of the rising flank. Again streamer-like and Townsend-like discharges are observe-able.

![Figure 5.5: Current through the test object, $I_{TO}$, as a function of time, $t$, as well as the corresponding voltage, $V$. Recorded at a positive dc voltage with a ripple of 46.0 %.
](image)

To further examine the bipolar discharge phenomenon the sample has been solely stressed with an ac voltage. The results, which are shown in Figure 5.6, indicate that one discharge ignites during each half cycle. The peak value of the ac voltage is 1.2 kV. This corresponds to a peak-to-peak value of 2.4 kV. Now, the dc component is subtracted from the voltage that corresponds to the discharge times series, which showed positive and negative discharges. The result is an ac voltage with a peak-to-peak value of 3.1 kV. Therefore, the peak-to-peak value of the dc voltage with a ripple of 46.1 % is bigger than the peak-to-peak value of the pure ac voltage. Consequently, from an ac perspective, the inception voltage can be reached in both half-cycles. It can therefore be concluded that the occurrence of discharges in both virtual half-cycles is an ac discharge behaviour i.e. the alternating field component is dominating the discharge process.

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33 If the dc component is virtually subtracted.
34 The word virtual has been used to quantify that those are not actual half cycles.
A different aspect in connection with the discharge frequency is the strong influence of the ripple on the time instances during which discharges can ignite. Figure 5.7 b) shows a 60 ms time series of the discharge current recorded in series with the test object. The voltage was set to -3 kV at a ripple of 2.5 %. If the ripple is enhanced to 4.6 %, while the voltage is kept at -3 kV, a strong reduction in discharge activity during the falling flank is visible as given in Figure 5.7 c) from 20 ms to 30 ms. This behaviour can also be observed at a higher peak value of the voltage as is shown for a ripple of 8.4 % at a peak value of -5 kV in Figure 5.7 d). Figure 5.7 a), which has been recorded at -2 kV, emphasizes that this effect is not caused by the inception voltage, which has to be below -2 kV.

\(^{35}\)Time instance refers to times within the 20 ms period of the rectified 50 Hz ac voltage.
5 Surface discharges in air

Figure 5.7: Current through the test object, $I_{TO}$, as a function of time, $t$, as well as the corresponding voltage, $V$. For a voltage and ripple of -2 kV and 2.5 % a) -3 kV and 2.5 % b), -3 kV and 4.6 % c), -5 kV and 8.4 % d).

Now this thesis will develop a possible explanation to describe the formerly observed phenomena. For this the equivalent circuit given in Figure 5.8 is used. The resistors $R_1$ and $R_2$ represent the surface resistance and the volume resistance of the dielectric. The capacitor $C_1$ is the stray capacitance of the arrangement and $C_2$ is the capacity of the dielectric. The sphere gap, $S_g$, indicates that the discharge will develop across the surface of the dielectric. The dotted components indicate that the equivalent circuit is composed of a chain of the networks to properly reflect the change of the components as the discharge advances across the surface. In general the surface resistance, $R_1$, and the volume resistance, $R_2$, are material dependent.
Now, three different scenarios based on the voltage can be examined. Those are the application of a dc voltage, an ac voltage and a combined ac and dc voltage. A pure dc voltage, \( V_{dc} \), implies that the capacitances \( C_1 \) and \( C_2 \) are not active. However, as a dc voltage has to be turned on they cannot be completely neglected. As \( C_1 \) is assumed to be small compared to \( C_2 \) the dominant charging process is that of \( C_2 \). If it is further assumed that the voltage distribution after turn on is mainly defined by the resistors, then two different possibilities have to be examined.

Firstly, if \( R_1 \) is bigger than \( R_2 \), then the voltage will drop across the surface of the dielectric. Hence, if the voltage is high enough discharges across the surface can ignite. This is illustrated in Figure 5.9 a). In this figure \( V_{Sgd} \) represents the voltage across the sphere gap in the case that discharges occur. This voltage drops to a residual voltage, \( V_{res} \), whenever the inception voltage, \( V_{inc} \), is reached and a discharge is assumed to ignite. \( V_{Sg0} \) is the progression that the voltage across the sphere gap would take in the absence of discharges. Continuous discharge activity might result in a change of the surface of the dielectric and therefore, its surface conductivity. This has for example been shown for ac stressed epoxy resin samples by Hudon et al. [114]. The authors reported a decrease of discharge activity over time, which finally resulted in a complete cessation of streamer-like discharges and a transformation to a glow discharge. The authors partially attributed the observed behaviour to a change in surface conductivity. Fromm [31] reported an increase of surface partial discharge activity over time for cellulose-3-acetate samples and a decrease of activity for polyethylene samples. Even though, not
explicitly stated the observed increase of discharge frequency might be caused by an increase of surface resistivity.

Secondly, if $R_2$ is bigger than $R_1$ discharges can ignite during the turn on of the voltage if $C_1$ is smaller than $C_2$ as the capacitances define the initial voltage distribution. Afterwards, the voltage across the surface of the dielectric decreases as the capacitance $C_2$ is charged. An illustration of the course of the voltage is given in Figure 5.9 b). One initial discharge is contained in the figure. However, if $C_2$ is smaller than $C_1$, while $R_2$ is bigger than $R_1$ no discharges can be observed as the initial voltage drop is mainly across $C_2$.

![Figure 5.9: Theoretical dc voltage behaviour for a surface discharge arrangement if the surface resistor, $R_1$, is bigger than the volume resistor, $R_2$, a) and vice versa b).](image)

At a pure ac voltage the voltage distribution is governed by the capacitance $C_1$ and $C_2$. As long as the stray capacitance, $C_1$, is smaller than the capacitance of the dielectric, $C_2$, discharges will commence across the surface of the dielectric. They are limited to the positive rising flank and to the negative rising flank. During the falling flanks a field reversal occurs and discharges cannot ignite as the inception voltage is not reached during the corresponding time instances.

At mixed voltages both behaviours, which have been explained under 1. and 2. are observable. Hence, again a differentiation based on the values of surface resistivity and volume resistivity has to be made. For simplification reasons the graphical representations have been obtained with a dc voltage superimposed with a 50 Hz ac voltage i.e. $v(t) = \dot{V}_{ac} \cdot \sin(\omega t) + V_{dc}$. Additionally, it has been assumed that a starting electron is always available, when the inception voltage, $V_{inc}$, is reached. Hence, a discharge ignites and the voltage drops to the residual voltage, $V_{res}$. In the first case it is assumed that $R_1$ is bigger than $R_2$. 

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If the ripple is small, i.e. below 2.4 %, continuous discharges, with respect to one period of the ac voltage can be observed. A corresponding voltage course for the case of discharges, $V_{\text{SGds}}$, and the absence of discharges, $V_{\text{SG0s}}$, are shown in Figure 5.10 a). The discharge activity might again decrease over time as in the pure dc case. If a medium ripple is applied, the discharge activity might cease during parts of the positive half-wave of the alternating voltage component due to the field reversal, similar as in the ac voltage case. Medium shall be defined as being bigger than the border given for small values of the ripple and smaller than the value required for discharge inception in both half-waves. A sample case is illustrated in Figure 5.10 b) by the voltage progressions $V_{\text{SGdm}}$ and $V_{\text{SG0m}}$. The main difference to the ac case is that the time instances during which discharges are absent are not constant but increase with an increasing ripple. If a large ripple is present on the dc voltage, then discharges can also ignite during the positive half-wave, as the positive inception voltage will be reached during the polarity reversal. An example case is depicted in Figure 5.10 b). The corresponding voltage progressions are represented by $V_{\text{SGdb}}$ and $V_{\text{SG0b}}$.

Figure 5.10: Theoretical ac+dc voltage behaviour for a surface discharge arrangement if the surface resistor, $R_1$, is bigger than the volume resistor, $R_2$. For a small ripple a) as well as for a medium and a large ripple b).

In the second case the resistor $R_2$ is assumed to be bigger than $R_1$. Again, no discharges, except during turn on, can ignite at a small and a medium ripple. However, if the capacitance $C_1$ is smaller than $C_2$ and a big ripple is used then discharges can ignite during both half-waves. This behaviour is illustrated in Figure 5.11 for a ripple of 2 % ($V_{\text{SGds}}$ and $V_{\text{SG0s}}$) and a ripple of 50 % ($V_{\text{SGdb}}$ and $V_{\text{SG0b}}$).
The results from the formerly presented simulations support the conclusion that positive and negative discharge pulses will commence if the peak-to-peak value of the ripple is at least equal to the ac peak-to-peak inception voltage. Furthermore, it has been shown that the reduction in discharge activity with an increased ripple is caused by the field reversal of the ac components, which are present on dc voltage.

The average pulse amplitude, $\bar{i}_p$, of Townsend-like discharges seems to stay constant at values of the voltage of -3 kV and -5 kV as shown in Figure 5.12 a). While Figure 5.12 b), indicates that streamer-like discharges show a tendency towards an increase of the average pulse amplitude for values of the ripple above 13.8 % for -3 kV and 0.8 % for -5 kV. However, due to the large stray of the data an interpretation of the behaviour of Townsend-like and especially streamer-like discharges is difficult.
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Figure 5.12: Average pulse amplitude, $\bar{i}_p$, as a function of the voltage ripple, $V_{R\%}$ for Townsend-like discharges a) and streamer-like discharges b).

The average pulse rise time, $\bar{t}_{rt}$, and the average pulse fall time as a function of the ripple are shown in Figure 5.13 and Figure 5.14, respectively. In general it can be stated that both, the rise time and the fall time are longer for Townsend-like discharges than for streamer-like discharges. There seems to be no influence of the voltage on the rise time and the fall time of both discharge types. The ripple does also have a neglect-able effect on the time attributes of the discharges. Nevertheless, these interpretations should be adopted with care as other tendencies, then the ones reported, might be invisible due to the large variation of the data.

Figure 5.13: Average pulse rise time, $\bar{t}_{rt}$, as a function of the voltage ripple, $V_{R\%}$ for Townsend-like discharges a) and streamer-like discharges b).
Based on these observations it can be stated that surface discharges should be evaluated at a ripple that is below 0.8 % if the negative dc voltage has been obtained by a half-wave rectification. This value is primarily related to the discharge frequency, which showed the most prominent change with respect to the ripple. The change of the discharge frequency has been explained with the polarity reversal of the ac components of the voltage. The influence of which is especially significant if the ac components have a peak-to-peak value, which is above the ac peak-to-peak inception voltage. In this case positive and negative discharges can ignite even though the voltage is unipolar. The behaviour of the average pulse amplitude, average pulse rise time and average pulse fall time do not challenge the derived 0.8 % criterion although the corresponding results are difficult to interpret.

5.1.2 Influence of the voltage on the discharge behaviour

In this subsection the influence of the voltage on the discharge behaviour is examined and the corresponding phase resolved partial discharge patterns are obtained. The test sample as per Figure 3.8 is stressed with a constant ripple of 0.6 % while the voltage is varied. Measurements were performed with aid of the PD-detector and the pulse-detector. Some of the pattern have already been published by the author [121]. However, no detailed explanation of the underlying physical processes has been given.

The ambient conditions showed a temperature of 19.0 °C, a relative humidity of 28.2 % and an air pressure of 1004.0 hPa. All environmental data is given as average values over the whole measurement duration.
The first pattern that can be observed is formed by a concentration of discharges of small magnitude in the vicinity of the maximum of the voltage. A corresponding pattern is shown in Figure 5.15 a).

![Figure 5.15: Discharge magnitude, Q, and ripple voltage, ΔV_{DC}, as a function of the phase angle, ϕ, recorded at -1.0 kV a). Current through the test object, I_{TO}, and voltage, V, as a function of time, t, b), as well as two magnified versions of the current c) and d).](image)

The pattern formed due to pulses with a short rise time and a large magnitude, as well as pulses with a comparatively longer rise time and shorter magnitude. Those are shown in Figure 5.15 c) and d). The first pulse has been referred to as a streamer-like pulse, whereas the second type has been called Townsend-like. Due to their different appearance it is possible that two different discharge mechanisms might be underlying. As the Townsend-like discharge shows a small plateau in the peak region of the pulse it resembles a glow discharge. It is therefore possible that the Townsend-like discharge is caused by a small glow discharge around the point electrode. Figure 5.15 b) furthermore indicates, that there seems to be a likelihood for larger pulses to ignite in the vicinity of the maximum of the voltage.

An enhancement of the voltage leads to a shift of the formerly reported pattern towards the zero crossing of the voltage, as is shown in Figure 5.16 a). The pattern shows a steeper rise, than decay. Additionally, a second group of discharges at a higher discharge magnitude is visible. A time-series of the discharge current, as illustrated in Figure 5.16 b), shows that larger pulse magnitudes occur in the rising flank of the ripple. In the same region, both Townsend-like and streamer-like discharges can be observed.
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Figure 5.16: Discharge magnitude, $Q$, and ripple voltage, $\Delta V_{DC}$, as a function of the phase angle, $\phi$, recorded at -1.75 kV a). Current through the test object, $I_{TO}$, and voltage, $V$, as a function of time, $t$, b).

At even higher voltage a third band of discharge activity with higher discharge magnitudes appears as is shown in Figure 5.17 a). Corresponding recordings of the discharge current reveal the presence of Townsend-like and streamer-like discharges. Those discharges are illustrated in Figure 5.17 c) and e). It can be reported that the pulses, which show peak values in the range of 150 $\mu$A are streamer-like discharges. Hence, the newly observed discharge concentration is formed due to streamer-like discharges, only.

Figure 5.17: Discharge magnitude, $Q$, and ripple voltage, $\Delta V_{DC}$, as a function of the phase angle, $\phi$, recorded at -2.16 kV a). Current through the test object, $I_{TO}$, and voltage, $V$, as a function of time, $t$, b) and d), as well as magnified versions of the current c) and e).

The last pattern that could be observed is shown in Figure 5.18 a). Two bands of discharge activity and two concentrations of discharges are visible. The lowest band, which has discharge magnitudes below 10 pC, has an enveloping function that shows a slightly higher discharge magnitude in the vicinity of the maximum of the voltage. The second band is located between 10 pC and 150 pC.
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This band appears as a flat band, which does not show any specific voltage dependence. However, if that band is analysed towards the number of discharges that occurred in a 10° window then a tendency is clearly visible as shown in Figure 5.18 b). The pattern has a higher number of discharges in the vicinity of the zero crossing of the ripple. An identical evaluation for the lower band did not reveal any specific tendency. This might be caused as the data partly contains background noise due to the higher input gain required.

The number of discharges has been indicated by different dot sizes i.e. the largest dots represent the highest number of discharges per 10° window.

Now, the two concentrations of discharges shall be further analysed. The concentrations are formed due to discharges in the nano coulomb range. They are located in the vicinity of the maximum of the voltage. It can be reported that their appearance comes together with a newly observable pulse type. Figure 5.19 a) and b) show this new pulse type. For reference towards the general pulse waveform a streamer-like discharge is shown in Figure 5.19 d).

![Figure 5.18: Discharge magnitude, Q, and ripple voltage, ΔV_{DC}, as a function of the phase angle, ϕ, recorded at -7.75 kV a), as well as an advanced version, which contains information about the discharge frequency b).](image-url)
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Figure 5.19: Current through the test object, $I_{TO}$, and voltage, $V$, as a function of time, $t$, a), c) as well as a magnified version of the current b) and d). New discharge pulse, e), and a magnified version of the latter, f), assumed to be a leader discharge.

To further examine the new pulse a magnified version of this pulse is given in Figure 5.19 e). It can be seen that the rise of this pulse occurs in three steps, which have been highlighted. The first step resembles the properties of a streamer-like discharge as is shown in Figure 5.19 f) (1). The second step shows a slightly steeper rise as compared to the first step (2). In the third step the pulse rises very fast to its maximum (3). The decay of the pulse is also characterized by three different slopes. At first the pulse decreases rapidly (4). This rapid decrease is followed by a plateau phase of almost constant current behaviour (5). Afterwards, the current decreases at a moderate rate (6). The overall decay appearance is similar to a type one Trichel pulse. This might indicate the presence of a strong secondary ionization mechanism.

In Subsection 2.1.3 of this thesis the concept of the leader discharge has been briefly explained. It is typical for negative surface leader discharges \(^{37}\) to propagate stepwise in form of streamer-leader transitions. Therefore, the following chain of events, which are illustrated in Figure 5.20, might take place during the rise of the depicted, uncategorised pulse.

\(^{37}\)see Section 2.4
Figure 5.20: Assumed sequence of surface leader discharge development.

The initial situation shows a rectangular surface with a point electrode, where no discharge takes place (0). At first streamer discharges ignite in the vicinity of the point electrode (1). The streamer discharges can transform into leader channels (indicated in red) and at their tips new streamers can ignite (2). The same processes are repeated. It is possible that not all leader channels develop further streamers (3). Afterwards, the discharge activity ceases as the electrical field falls below a critical value to sustain the discharge. Despite the illustrated radial leader activity, it has to be noted that it is also possible that only a single leader channel might develop from the point electrode.

Larigaldie [140] conducted surface discharge experiments with a test setup that enforced a lateral propagation of the discharge. The presented graphs of the discharge current as a function of time showed an identical behaviour during the pulse decay phase as presented in Figure 5.19. Based on this similarity it is likely that a lateral spread i.e. development of a single channel of the discharge occurred in the present experiments as well.

The former findings are now summarized and afterwards a conclusion is drawn.
Firstly, the unknown discharge develops in steps, as has been argued based on Figure 5.19. Secondly, pulses with similar appearances during the decay phase have been reported by other authors, which declared them as leader discharges. Thirdly, it is one common feature of leader discharges to propagate in steps. It is therefore the authors opinion, that the pulse depicted in Figure 5.19 e) corresponds to a single channel, stepped leader discharge.

Now, a hypothesis with respect to the different observable discharge magnitudes in Figure 5.19 a) can be made. In general the charge related to a discharge is the time integral of the current of this discharge. Hence, if for example amplitude or duration of a pulse are varied the charge changes as well. With respect to a stepped leader, a variation of steps thus might lead to a variation of charge. It is therefore, plausible that the bands and concentrations of discharges as per Figure 5.18 a) correspond to different elongations of streamers and leaders as well as glow discharges. That means that the two lower bands are formed due glow discharges and the expansion of streamers whereas the concentrations are due to leader discharges, which develop in two or three steps. Support to this hypothesis is given by a charge calculation\(^{38}\) of four characteristic pulses, which have been recorded at the same voltage level. These pulses are graphically represented in Figure 5.21 a) and b)\(^{39}\). The pulse in black is a leader discharge, which developed in three steps. The charge of this pulse has been calculated to be 4.6 nC. This charge corresponds well with the upper concentration of discharge magnitudes in Figure 5.18 a). The pulse in dark grey is a leader discharge, which developed in two steps. The charge of this pulse has been calculated to be 1.4 nC. This charge fits the lower concentration of discharge magnitudes in Figure 5.18 a). The light grey pulse is a streamer-like discharge with a charge of 0.1 nC. This charge is a good fit to the upper band of discharges in Figure 5.18 a). The red pulse is a Townsend-like discharge (glow discharge), which has a charge of 1.5 pC. This value of charge corresponds well with the lower band of discharges in Figure 5.18 a).

\(^{38}\)The charge has been calculated with a time integral in form of a built-in MATLAB function called trapz.

\(^{39}\)The y-axis on the right side of the figure is only related to the waveform in red. All other curves belong to the left y-axis.
Therefore, if a negative dc voltage that contains a ripple due to a half-wave rectification is applied to a surface discharge arrangement mainly three different patterns can be observed. The first pattern is an onset pattern that shows a concentration of discharges in the maximum of the applied voltage. The second pattern is characterized by a shift of the former pattern towards the zero crossing of the voltage. The last pattern shows additional bands and concentrations of discharges, which have the tendency to be located in the vicinity of the maximum of the applied voltage or have an enveloping function that is higher in the maximum of the voltage than in the minimum. The appearance of more discharge bands and concentrations with increasing voltage is attributed towards the evolvement of the discharge mechanisms. It starts with a glow discharge, which can be recorded as Townsend-like discharge pulses. They can be accompanied by streamers of short elongation. The corresponding recordable pulses are small streamer-like discharges. Furthermore, larger streamer-like discharges can be observed, which represent a further elongation of the streamers. Finally, leader discharges, which propagate in several steps can be recognized.

**5.2 Surface discharges at positive voltage polarity**

In this section the behaviour of the surface discharge arrangement as per Figure 3.8 has been analysed with respect to a positive dc voltage that has been obtained
by a half-wave rectification of an ac voltage. The dielectric barrier used is a laminated paper of type PF CP 201. It is of quadratic shape, with a length of 70 mm. Its thickness is 0.5 mm. The dielectric constant of the material is 5.

### 5.2.1 Influence of the voltage ripple on the discharge behaviour

In this subsection the influence of the ripple on the discharge behaviour is evaluated by means of four characteristic discharge parameters. The parameters are the discharge frequency, $f_d$, the average pulse amplitude, $\bar{\tilde{i}}_p$, the average pulse rise time, $\bar{t}_{rt}$, and the average pulse fall time, $\bar{t}_{ft}$. The parameters have been obtained by analysing ten, 20 ms seconds time-series of the discharge current. The time-series have been recorded at an applied voltage of 3 kV and 5 kV with the aid of the pulse-detector at different values of the ripple. For the behaviour of the discharge frequency with respect to a varying ripple some results have already been published in a paper by the author [121].

The ambient conditions showed a temperature of 19.6 °C, a relative humidity of 27.5 % and a pressure of 995.7 hPa. All environmental data is given as average values over the whole measurement duration. Again, two different pulses could be observed. These are streamer-like and Townsend-like discharges. As in the previously reported evaluations the pulse type has been differentiated according to the rise time of the pulses. Two typical pulses are shown in Figure 5.22, where a Townsend-like discharge is given in a) and a streamer-like discharge in b).

![Figure 5.22: Current through the test object, $I_{TO}$, as a function of time, $t$. The rise time evaluation of a Townsend-like pulse, a), and a streamer-like pulse, b) is indicated.](image-url)
The Townsend-like discharge shows a rise time of 329 ns and the streamer-like discharge has a rise time of 75 ns. At negative polarity the border between Townsend-like and streamer-like discharges surface discharges was set to a rise time of 80 ns. However, at positive polarity pulses might occur, which show a small Townsend-like pre-pulse that enhances the rise time in such a way that the overall pulse is counted as a Townsend-like pulse even though its visual appearance is more streamer-like, as is indicated in Figure 5.23 a). If this pre-pulse is removed from the rise time estimation it shows a streamer-like behaviour as can be seen in Figure 5.23 b). Hence, due to the development of streamers from glow discharges (Townsend-like pulses) enhanced rise times can be observed. It has therefore been decided to increase the rise time border to 120 ns. To obtain comparable results the evaluation has also been performed at the original border of 80 ns.

The discharge frequency as a function of the ripple for Townsend-like and streamer-like discharges is shown in Figure 5.24 a) and b), respectively. It is clearly visible that the general tendencies of the discharge frequency of Townsend-like discharges are similar for 3 kV and 5 kV irrespective of the rise time border. The discharge frequency stays nearly constant for values of the ripple that are smaller than 0.8 % and decreases almost constantly for higher values of the ripple. Streamer-like discharges show similar tendencies for 3 kV and 5 kV but they are dependent upon the rise time border. If the rise time border is set to 80 ns, strong fluctuations and large variances make an interpretation below 0.8 % difficult. However, up to a value of 0.8 % ripple the discharge frequency is in the
range of 20 to 100 discharges per second. This means that between zero and two discharges occur every 20 ms period of the voltage or on average one discharge. Compared to Townsend-like discharges, which occur at a minimum ten times as often, those are not significant. The only important information that can be drawn is that streamer-like discharges can occur and are not absent. At higher values of the ripple an increase in streamer-like discharge frequency can be observed. If the rise time border is set to 120 ns, more discharges are counted as streamer-like and consequently the discharge frequency of Townsend-like discharges is reduced. Streamer-like discharges show again strong fluctuations for values of the ripple that are below 0.8 %. At higher values their activity stays nearly constant. The streamer-like discharge frequency behaviour is nearly identical for both selected rise time borders if the ripple is bigger than 0.8 %. If the behaviour of Townsend-like and streamer-like discharges are compared, then a transformation from Townsend-like domination to a combined Townsend-like and streamer-like discharge activity with increasing ripple is observable. The increased ripple seems to hinder the development of Townsend-like discharges. Streamer-like discharges are favoured (80 ns rise time border) or are at least unaffected (120 ns rise time border).

![Figure 5.24: Discharge frequency, $f_d$, as a function of the voltage ripple, $V_{R\%}$. Townsend-like discharges are given in a) and streamer-like discharges in b).](image)

The two main aspects, which can be taken from the former evaluation are the reduction of Townsend-like discharge activity with increasing ripple and the contrary behaviour of streamer-like discharges. These aspects shall now be further analysed.

A possible explanation for the reduction of Townsend-like discharge activity
might, as in the negative polarity case, be found with aid of the equivalent circuit depicted in Figure 5.8. It is assumed that $R_1$ is bigger than $R_2$ and $C_2$ is bigger than $C_1$. If now a combined voltage is applied, then the discharge activity will in general be reduced with increasing ac components. This is due to the polarity reversal of the ac components as was shown for a negative polarity of the dc component in Figure 5.10 b). A general reduction will also include Townsend-like discharges.

The effect of the ripple on the streamer-like discharges could be caused by an increased surface charge accumulation with increased ac components of the applied voltage. Experiments [141] with polyethylene have shown that at combined voltages the dc component is responsible for charge accumulation inside of the dielectric, whereas the ac component causes charge accumulation in the vicinity of the electrodes. This surface charge could enhance the field strength and lead to a higher streamer-like discharge activity due to enhanced photoionisation.

As no significant difference resulted from the two selected rise time borders, it has been decided to continue the evaluation with a rise time border of 80 ns to maintain comparability towards negative surface discharges.

The average pulse amplitude as a function of the ripple is depicted in Figure 5.25 a) for Townsend-like discharges and in Figure 5.25 b) for streamer-like discharges. It can be seen that the Townsend-like discharges are unaffected by the ripple except for two points, which are treated as outliers. On the contrary the streamer-like discharges show a tendency to increase in magnitude with increasing ripple. This tendency should however be carefully adopted as the large stray, especially for tests with a peak value of 5 kV, could conceal a different behaviour. On the other hand an increased pulse amplitude would support an enhanced field strength due to surface charge accumulation by the increased ac components.
5 Surface discharges in air

Figure 5.25: Average pulse amplitude, $\bar{i}_p$, as a function of the voltage ripple, $V_{R\%}$. Townsend-like discharges a) and streamer-like discharges b).

The average pulse rise and fall time as a function of the voltage ripple are shown in Figure 5.26 and Figure 5.27, respectively. It can be observed that the rise time and fall time of Townsend-like discharges decrease with increasing ripple, whereas streamer-like discharges seem to be unaffected by the ripple.

Figure 5.26: Average pulse rise time, $\bar{t}_{rt}$, as a function of the voltage ripple, $V_{R\%}$. Townsend-like discharges a) and streamer-like discharges b).

Figure 5.27: Average pulse fall time, $\bar{t}_{ft}$, as a function of the voltage ripple, $V_{R\%}$. Townsend-like discharges a) and streamer-like discharges b).
This subsection can be concluded by stating that based on the presented evaluation partial discharge tests for surface discharges at positive dc voltage should be carried out with a ripple of below 0.8 %. This border is mainly caused by the polarity reversal of the ac components of the voltage, which forces the electric field below the inception field strength. Furthermore, an increased surface charge accumulation due to the increasing ac components with increasing ripple can be attributed to an altered electric field.

### 5.2.2 Influence of the voltage on the discharge behaviour

In this subsection the influence of the voltage on the discharge behaviour is examined. The test sample shown in Figure 3.8 is therefore stressed with a positive voltage at a constant ripple of 0.6 %. This is again the minimum ripple that is required to produce a visible pattern throughout the voltage range. Some of the results have already been published by the author in [121]. However, no detailed explanation of the underlying physical processes has been given as of yet. The ambient conditions showed a temperature of 19.5 °C, a relative humidity of 27.1 % and a pressure of 999 hPa. All environmental data is given as average values over the complete measurement duration.

The first pattern that can be observed is shown in Figure 5.28 a). A concentration of discharges between a phase angle of 60 ° and 240 ° can be identified. In general, higher discharge magnitudes occur in the vicinity of the maximum of the voltage than in the minimum. This behaviour can also be observed, when the discharge current, as per Figure 5.28 b), is examined. If compared to the onset pattern of negative surface discharges a much lower discharge rate can be observed. At negative polarity, 1 kV and 0.6 % ripple about 14000 discharges took place whereas at positive polarity and the same voltage conditions only 7000 discharges ignited during the same observation time of 120 s.
5 Surface discharges in air

Figure 5.28: Discharge magnitude, $Q$, and ripple voltage, $\Delta V_{DC}$, as a function of the phase angle, $\varphi$, recorded at 1.07 kV a). Current through the test object, $I_{TO}$, and voltage, $V$, as a function of time, $t$, b), as well as a magnified version of the current c).

At a higher voltage the discharge activity strongly increases as is shown in the $Q(\varphi)$-diagram depicted in Figure 5.29 a). The highest discharge magnitudes are now concentrated to the left of the maximum of the voltage. Their maximum is in the vicinity of the zero crossing of the ac components of the voltage.

Figure 5.29: Discharge magnitude, $Q$, and ripple voltage, $\Delta V_{DC}$, as a function of the phase angle, $\varphi$, recorded at 2.2 kV a). Current through the test object, $I_{TO}$, and voltage, $V$, as a function of time, $t$, b) as well as magnified versions of the current c) and d).

Additionally, it can be shown that the overall discharge activity is higher in the regions of a high dV / dt rate of the voltage than throughout other time instances. To this end the $Q(\varphi)$-diagram of Figure 5.29 a) has been modified to include an information about the number of discharges per 10° window. The results are depicted in Figure 5.30. It can be seen that the highest number of discharges is located between the minimum and the maximum of the voltage.
Both observed patterns can be explained with aid of the equivalent circuit, which is shown in Figure 5.8. In the non-stationary state this circuit leads to an exponential charging process. The voltage components are hence multiplied by an exponential term with a relaxation time constant. In general it can be stated that whenever the voltage across the sphere gap reaches the discharge inception voltage, $V_{\text{inc}}$, and a starting electron is available a discharge across the surface of the dielectric can ignite. The ripple will show a varying $\frac{dV}{dt}$ rate, which is highest during the recharging of the capacitive elements. The recharging starts, when the positive half wave of the ac voltage becomes higher than the capacitor voltage. During the recharging process the voltage across the sphere gap, i.e. the surface, can build up much faster. Consequently, the inception voltage is reached earlier as during the remainder of a 50 Hz period. This behaviour is shown in Figure 5.31 a). The voltage distributions shown therein have been obtained by means of a Matlab / Simulink based simulation of the equivalent circuit. The dc voltage, $V_{\text{dc}}$, has an amplitude of 1.0 kV and a ripple of 0.6 %. The inception voltage, $V_{\text{inc}}$, has been set to 450 V. For simplification it has been assumed that a starting electron is always available. The enhanced likelihood of discharges occurring during time instances, which are located a bit prior to the minimum, between minimum and maximum and slightly after the maximum of the dc voltage is clearly shown. The consequence is a discharge pattern as given in Figure 5.28.
At a peak value of the dc voltage of 2.2 kV a much higher discharge frequency is observed from the simulation as indicated in Figure 5.31 b). Now, the enhanced discharge activity is limited to the area between the minimum and maximum of the dc voltage. This explains the location of the higher number of discharges in Figure 5.30. An explanation for the behaviour of the discharge magnitudes can be found by considering the availability of starting electrons. In the simulations it has been assumed that they are always available, when the voltage reaches the inception voltage. This is however just a simplification as their availability is of stochastic nature [123]. Consequently, if no starting electron is available during the time the inception voltage is reached, then the voltage across the surface of the dielectric increases further. If now a starting electron becomes available the discharge ignites at a voltage that is above the inception voltage. Therefore, a difference between inception and ignition voltage exists. This difference is referred to as overvoltage [91]. It has been shown [142]–[144], that the discharge magnitude, is proportional to the overvoltage. Hence, the ripple on the dc voltage and the associated faster rise of the voltage between minimum and maximum of the voltage enforces higher discharge magnitudes in this area. This explains the formation of the pattern as per Figure 5.29.

If the voltage is further enhanced the observed discharge magnitudes are getting lower with increasing voltage, while their frequency of occurrence increases. This behaviour is illustrated in Figure 5.32. Part a) of the Figure shows a \( Q(\varphi) \)-diagram that has been recorded at 3.65 kV, whereas part b) has been recorded at 6.8 kV. The number of Townsend-like discharges increases from 66 per 50 Hz
period to 163 per 50 Hz period. The streamer-like discharges are comparable and are in the range of five discharges per 50 Hz period. It is important to report that the recordings have been made at identical input gain i.e. the reduction of discharge magnitudes is not caused by a change of the gain and the increased frequency is not due to an increased background noise.

Figure 5.32: Discharge magnitude, \( Q \), and ripple voltage, \( \Delta V_{DC} \), as a function of the phase angle, \( \varphi \), recorded at 3.65 kV a) and 6.8 kV b).

To further access this behaviour the underlying discharge current is inspected. It is evident from Figure 5.33 that the discharge current shows an altered behaviour at 6.8 kV as compared to 3.65 kV. Discharges of small amplitudes in the range of some hundred nano ampere are frequently occurring as is indicated in Figure 5.33. Their appearance is similar to that of burst pulses from positive corona. It shall be recalled here that burst pulses develop into the positive pulsating glow discharge as was shown in Subsection 4.2.2. It is therefore the authors opinion that the discharge magnitudes shrink as a surface glow discharge in the vicinity of the point electrode develops.
Figure 5.33: Current through the test object, $I_{TO}$, and voltage, $V$, as a function of time, $t$, a) and c) as well as a magnified version of the current b) and d).

In this subsection two patterns have been derived for positive surface discharges at dc voltages that contain a ripple due to a half wave rectification. The first pattern, which can be observed at discharge onset, is characterized by a broad spread of discharges around the maximum of the voltage. It has an envelope function that follows the progression of the voltage. The second pattern appears as a dense concentration of discharges between the minimum and the maximum of the voltage. The highest discharge magnitudes occur in the virtual zero crossing of the ripple.

5.3 Summary

In this chapter the discharge behaviour of a surface discharge arrangement has been analysed with respect to a negative and positive dc voltage with a varying ripple. Furthermore, characteristic phase resolved partial discharge patterns have been obtained and explained based on the underlying physical effects. The results can be summarized as follows:

At negative polarity it has been shown that a dc voltage with a ripple below 0.8 % should be used to carry out partial discharge tests. Above this value the electric field is altered, which results in a changed voltage distribution and the ac components will undergo a polarity reversal. This leads to a reduction in the discharge frequency with increasing ripple. Furthermore, it has been demonstrated
that if the peak-to-peak value of the ripple is, in terms of voltage, equal to the ac peak-to-peak inception voltage both positive and negative discharges can be observed irrespective of the dc voltage polarity. Based on the 0.8 % criterion characteristic phase resolved partial discharge patterns have been obtained. The ripple required to produce a visible effect throughout the complete voltage range tested is 0.6 %. Three characteristic patterns could be derived. The first pattern is characterised by a band of discharge magnitudes in the small pico coulomb area. The band has an enveloping function, which follows the waveform of the voltage. The highest discharge magnitudes are therefore located in the vicinity of the maximum of the voltage. The second pattern is nearly identical to the first pattern, except that it is shifted towards the virtual zero crossing of the ripple. The third pattern is composed of multiple bands and concentrations of discharges. The highest discharge magnitudes align with the maximum of the voltage.

At positive polarity the difference in behaviour of Townsend-like and streamer-like discharges is more obvious than for the negative polarity case. For example the discharge frequency of Townsend-like discharges decreased when the ripple was increased above 0.8 %, whereas streamer-like discharges showed an increased activity. The ripples influence on the Townsend-like discharges has been argued with the occurring polarity reversal of the ac components. The enhanced streamer-like activity was attributed towards an increased surface charge accumulation and a potentially increased photoionisation. Based on the experiments a maximum ripple of 0.8 % has been recommended for dc partial discharges with respect to surface discharges. A ripple of 0.6 % has been used to acquire characteristic phase resolved partial discharge patterns. Two different patterns can be reported with respect to a positive dc voltage containing a ripple. The first pattern is characterized by a concentration of discharges, which stretch between the minimum of the voltage and about 110 ° past the maximum of the voltage. The highest discharge magnitudes align with the maximum of the voltage. The second pattern shows a hill like formation of discharge magnitudes located between minimum and maximum of the voltage. The maximum of the discharge magnitudes can be found in the vicinity of the zero crossing of the ripple. The observable discharge magnitudes shrink with an increasing voltage. This observation has been attributed towards the development of a glow discharge around the point electrode. In the
next chapter the behaviour of a test sample, which is subjected to internal partial discharges is analysed.
In this chapter the behaviour of a test arrangement that is subjected to internal partial discharges due to a dc voltage, that has been obtained by a half-wave rectification, is analysed. The test sample is constructed as described in Section 3.4. A graphical representation of the test sample can be found in Figure 3.7. The test object is at first stressed with a constant peak value of the dc voltage, while the ripple is varied to examine the ripples influence on the discharge behaviour. The corresponding procedure, results and discussion are given in Section 6.1. The same arrangement is afterwards stressed at a fixed ripple and characteristic phase resolved partial discharge patterns for internal partial discharges are obtained. The observed patterns and their formation cause are given in Section 6.2. Due to the symmetry of the test arrangement it has been stressed with a positive voltage only. Orienting examinations with negative polarity yielded comparable results. This chapter is hence, not subdivided according to the polarity of the voltage.

6.1 Influence of the voltage ripple on the discharge behaviour

In this section the influence of the voltage ripple on the discharge behaviour is assessed by examining the evolution of four characteristic discharge parameters with respect to a varying ripple. These are the discharge frequency, \( f_d \), the average pulse amplitude, \( \bar{i}_p \), the average pulse rise time, \( \bar{t}_{rt} \), and the average pulse fall time, \( \bar{t}_{ft} \).

The existence of two different discharges can be seen and have also been reported by other authors [90], [91] as described in Chapter 2.3. These are Townsend-like and streamer-like discharges. Their appearance, which is for reference depicted in Figure 6.1, is similar to the Townsend-like and streamer-like pulses that were already discussed in Chapter 5.
The evaluation of the characteristic discharge parameters has again been subdivided based on the pulse type. Differentiation of the pulses has been performed due to the different rise times of the pulses. The border between pulse types has been set to 80 ns i.e. pulses with a rise time below 80 ns are counted as streamer-like and above 80 ns are counted as Townsend-like. Furthermore, two different voltage levels, of 2.5 kV and 5.0 kV, have been selected for the evaluation.

The discharge frequency, $f_d$, as a function of the voltage ripple, $V_{R\%}$, is given in Figure 6.2. The behaviour of Townsend-like discharges is shown in a) and for streamer-like discharges in b). In general the discharge activity is higher for 5.0 kV than for 2.5 kV, irrespective of the pulse type. The discharge frequency of Townsend-like discharges seems to be unaffected by the ripple for a peak value of the voltage of 2.5 kV. This behaviour could not be observed for 5.0 kV. Here, the discharge frequency decreases for higher values of the ripple.

Streamer-like discharges seem to be even more influenced by the ripple. For both voltage levels an increase in discharge activity for a ripple bigger than 0.4 % could be observed. It is especially true at 2.5 kV, where no streamer-like discharges could be observed below 0.4 %. At this point it is necessary to report the findings of Fromm [31] and Morshuis [90]. Fromm evaluated discharge pulses at pure dc voltages and Morshuis at pure ac voltages. The former reported only Townsend-like discharges above PD onset, whereas the latter reported only streamer-like discharges. This can be taken as a first indicator for the difference between ac and dc caused discharges. The results of both publications
where related to non-aged samples. Fromm, furthermore reported the onset of streamer-like discharges with enhanced voltage. They were active in parallel to Townsend-like discharges. Those results fit well with the findings of this study for values of the ripple that are below or equal to 0.4 %. Here, solely Townsend-like discharges were active at 2.5 kV and streamer-like discharges became also active after a voltage increase to 5.0 kV. Above 0.4 % the observations made in this thesis do not coincide with those made by Fromm. Here, streamer-like and Townsend-like discharges are active in parallel even at a voltage just above onset. The presence of streamer-like discharges might hence indicate a more ac like behaviour. The ripple of 0.4 % should therefore be a border between dc field behaviour and mixed ac and dc field behaviour. The results of both authors consequently indicate that the addition of ac components to the dc voltage influence the onset conditions for streamer-like discharges, which for the first time could be experimentally proven in this work.

In the following it is further examined how the ripple influences Townsend-like and streamer-like discharges with respect to their discharge frequency. To this end the time and magnitude dependencies between pulses have been analysed at different values of the ripple. The time between a pulse, \( p_i \), and the prior pulse, \( p_{i-1} \), is calculated by:

\[
\Delta t_p = t_{p_i} - t_{p_{i-1}} \tag{6.1}
\]

The corresponding pulse amplitude difference is given by:

\[
\Delta \hat{p}_p = |\hat{p}_i - \hat{p}_{i-1}| \tag{6.2}
\]
The underlying time series of the discharge current are the same that have been used for the evaluation of the discharge behaviour, i.e. discharge frequency, average pulse amplitude etc..

The pulse amplitude difference, $\Delta \hat{i}_p$, as a function of time between two consecutive pulses, $\Delta t_p$, is shown in Figure 6.3. The voltage has a peak value of 5.0 kV and a ripple of 0.2 % a), 0.7 % b), 8 % c) and 24.6 % d). A general tendency for a reduction of the time between discharges with increasing ripple is visible. This is of particular interest as with an increased ripple a reduction of the time instances during which discharges ignite can be reported as is shown in Figure 6.4.

Figure 6.3: Pulse amplitude difference, $\Delta \hat{i}_p$, as a function of the time between two consecutive pulses, $\Delta t_p$, recorded at 5.0 kV and a ripple of 0.2 % a), 0.7 % b), 8.0 % c) and 24.6 % d).

To further emphasize this reduction and to show that the cut-off in Figure 6.4 d) at 54 $\mu$A does not hide any discharge pulses, a magnified version of this time series is given in Figure 6.5. Here, a simultaneous recording, which has been obtained with a second channel of the pulse detector is shown in part b). This channel has been set to a different input gain to avoid a cut-off of the discharge current. The drawback is a lower resolution due to a changed quantization.
Figure 6.4: Current through the test object, $I_{TO}$, as a function of time, $t$, as well as the corresponding voltage, $V$ recorded at 5.0 kV and a ripple of 0.2 % a), 0.7 % b), 8 % c) and 24.6 % d).

The former observations indicate that the ripple contributes in two ways. Firstly, the time between discharges is reduced and secondly the time instances during which discharges can ignite are limited. The latter shall now be further examined. The change rate of the voltage is especially high in the area between the virtual zero crossing of the ac components of the voltage and the maximum of the voltage. It is therefore highly probable that the inception field strength is reached but no starting electron is available. Hence, an overvoltage can develop. Devins [91] reported that streamer-like discharges ignite at higher overvoltages than Townsend-like discharges. The increase of streamer-like discharge activity with increasing ripple might therefore be caused by higher overvoltages due to the increased ripple.
Figure 6.5: Current through the test object, $I_{TO}$, as a function of time, $t$, as well as the corresponding voltage, $V$, recorded at 5.0 kV and a ripple of 24.6 %.

The average pulse amplitude, $\bar{i}_p$, as a function of the ripple, $V_{R\%}$, is depicted in Figure 6.6. If minor fluctuations are neglected, then the discharge current seems to increase with higher values of the ripple for Townsend-like discharges, as is shown in Figure 6.6 a) and for streamer-like discharges in Figure 6.6 b). The higher discharge magnitudes might again be caused by an increase in overvoltage with higher ripples. Devins [91] reported a proportionality of pulse height and overvoltage for Townsend-like discharges. He also reported an increase of the discharge magnitude with increasing overvoltage for streamer-like discharges. Unfortunately, the results have been expressed in Coulombs and are therefore, not directly related to the pulse height, but rather to the total area covered by the waveform of the pulse. Bartnikas and Novak [142] showed that space charge affected discharges i.e. streamers show a tendency towards higher pulse amplitudes with increasing overvoltage. The results obtained here indicated that the increase of the pulse amplitude with increasing ripple might be caused by increased overvoltages.
6 Internal partial discharges

Figure 6.6: Average pulse amplitude, \( \overline{\epsilon_{p}} \), as a function of the voltage ripple, \( V_{R\%} \) for Townsend-like discharges a) and streamer-like discharges b).

The average pulse rise time, \( \overline{t_{rt}} \), as a function of the ripple, \( V_{R\%} \), is shown in Figure 6.7. Townsend-like discharges show a decreased rise time with increasing ripple. This behaviour could be observed irrespective of the amplitude of the voltage. Bartnikas and Novak [142] reported reduced rise times of discharges that are governed by the Townsend mechanism at enhanced overvoltages. The decrease might therefore again be caused by the higher overvoltages that are to be observed with a higher ripple. For streamer-like discharges the average pulse rise time seems to be independent of the ripple. This observation could be made for 2.5 kV and for 5.0 kV.

Figure 6.7: Average pulse rise time, \( \overline{t_{rt}} \), as a function of the voltage ripple, \( V_{R\%} \) for Townsend-like discharges a) and streamer-like discharges b).

The average pulse fall time, \( \overline{t_{ft}} \), as a function of the ripple, \( V_{R\%} \), is shown in Figure 6.7. A decrease of the fall time with increasing ripple can be reported for Townsend-like discharges. Streamer-like discharges seem to be unaffected by the ripple and the voltage.
6.2 Influence of the voltage on the discharge behaviour

In this section the influence of the voltage on the discharge behaviour is examined and the corresponding phase resolved partial discharge patterns are derived. The test sample as per Figure 3.8 is stressed with a constant ripple of 0.4 % while the voltage is varied. Measurements were performed with the aid of the PD-detector and the pulse-detector. The ambient conditions showed a temperature of 21.2 °C, a relative humidity of 33.8 % and an air pressure of 992.3 hPa. All environmental data is given as average values over the whole measurement duration.

The first pattern that can be observed is shown in Figure 6.9 a). A concentration of discharge activity between a phase angle of about 60 ° to about 120 ° can be recognized in the range of 1 pC to 10 pC. The highest discharge magnitudes are located in the vicinity of the maximum of the voltage, whereas lower magnitudes appear close to the minimum. A second concentration in the same phase angle range for discharge magnitude values below 0.2 pC is also visible. Again, the discharge magnitudes in the vicinity of the maximum of the voltage are higher than in the minimum. Despite the two mentioned concentrations,
there appears to be a general tendency for the magnitudes of the discharges to be related to the instantaneous value of the voltage. Similar observations have been made by Gutfleisch and Niemeyer [145] for ac voltages. They stated that the proportionality of the maximum of the discharge magnitude to the voltage is one typical feature of internal partial discharges.

A 20 ms recording of the current measured in series to the test object, which is depicted in Figure 6.9 b), indicates that discharges with higher pulse amplitudes appear in the vicinity of the maximum of the voltage. It can furthermore be reported that only Townsend-like discharges were active at the selected voltage. This observation was expected, as it was already shown in Section 6.1 for 10, 20 ms time series that at a ripple of 0.4 % and a peak value of 2.5 kV only Townsend-like discharges are active. A Townsend-like discharge pulse is given in Figure 6.9 c).

![Figure 6.9: Discharge magnitude, Q, and ripple voltage, ∆V_{DC}, as a function of the phase angle, ϕ, recorded at 2.45 kV a). Current through the test object, I_{TO}, and voltage, V, as a function of time, t, b) as well as a magnified version of the current c).](image)

An enhancement of the voltage leads to a pattern as per Figure 6.10 a). The pattern itself appears as a hill like structure. The rising flank stretches from about 90 ° to 120 °. The falling flank extends from 120 ° to about 150 °. The prominent discharges extend from about zero crossing of the ripple towards the maximum of the ripple, which is emphasized in a magnified version of the pattern as shown in Figure 6.11.
6 Internal partial discharges

Figure 6.10: Discharge magnitude, $Q$, and ripple voltage, $\Delta V_{DC}$, as a function of the phase angle, $\varphi$, recorded at 5.0 kV a). Current through the test object, $I_{TO}$, and voltage, $V$, as a function of time, $t$, b) as well as a magnified version of the current c).

Figure 6.11: Discharge magnitude, $Q$, and ripple voltage, $\Delta V_{DC}$, as a function of the phase angle, $\varphi$, recorded at 5.0 kV.

Additionally, a new concentration of discharges in the nC range can be reported. They are located in the vicinity of the maximum of the voltage. A corresponding time series of the discharge current, which is shown in Figure 6.10 b) and c), indicates that this new concentration of discharges is caused by strong streamer-like discharges. Pulses with a similar appearance have been reported by Morshuis [90]. He categorized them as Townsend-like pulses with an overshoot. They are therefore, mainly governed by the Townsend mechanism and not as proposed in this thesis by photoionisation. Due to the discrepancy in pulse characterization those pulses shall be further analysed to clarify the underlying discharge mechanism. If the behaviour during the rise of the pulse, as per
Figure 6.10 c), is examined then a change in the current curve during the rising flank can be observed. A clearer picture of this behaviour can be seen in Figure 6.12 a) and b).

At first the current increases moderately for about 150 ns until a very steep rise commences. It is therefore possible that the active discharge mechanism changes form a Townsend-like discharge to a streamer-like discharge during the rise of the pulse. Support for this interpretation is given by the results reported by Devins [91]. In this paper the transition from Townsend-like to streamer-like discharges has been discussed. Oscilloscope recordings have been presented, which show the ignition of a streamer-like discharge from the rising flank of a Townsend-like discharge. Devins explained this transition with a critical number of avalanches that is required to build up a space charge that enhances the electric field and gives rise to an increased ionization, which enables streamer inception. He furthermore argued that a transition from a Townsend-like discharge to a streamer-like discharge is consequently dependent on the overvoltage, which is caused by the relation between successive avalanches and the overvoltage. For the purpose of further illustration of the interaction of Townsend-like and streamer-like discharge a Townsend-like discharge has been added to Figure 6.12. The rising flank of this pulse resembles the moderate current increase well. In classical streamer theory successive avalanches governed by the Townsend mechanism are usually assumed as a precursor for streamer inception due to the required space
charge enhanced field strength [146]. It is therefore the authors opinion that the discharge should be counted as a streamer-like discharge and not as a Townsend-like discharge.

Despite the previous findings it could still be possible that the observed large streamer-like discharges are caused by an external, unintended corona. It is however obvious from the third pattern, which is shown in Figure 6.13, that those pulses are not caused by a corona due to their shift towards the zero crossing. If those pulses were corona discharge pulses an enhancement of the voltage would lead to a spread towards the left and the right of the maximum of the voltage as has been shown in Section 4.2. The pattern itself is characterized by a shift of the previous discharge concentrations towards the virtual zero crossing of the ripple. The shift can be explained with aid of the equivalent circuit, which is shown in Figure 2.7. It has to be noted that this equivalent circuit is identical to the equivalent circuit, which has been presented for surface discharges. Only, the subscripts of the passive components have to be swapped. The simulation results are given in Figure 6.14. Here, part a) represents the conditions before the shift of the pattern. It has been assumed that a certain time lag exists before a starting electron is available. This results in higher overvoltages in the vicinity of the maximum of the voltage. As the discharge magnitude is proportional to the overvoltage [91] higher discharge magnitudes are observed for discharges that occur in the vicinity of the maximum of the voltage. Part b) of Figure 6.14 shows the results for a voltage that is high enough to shift the pattern to the left of the maximum of the voltage into the direction of the virtual zero crossing of the ripple. Due to the enhanced voltage the time-lag between discharges is reduced. This is caused by a faster increase of the voltage and a faster availability of starting electrons. The highest overvoltages are therefore shifted to regions where the change of the voltage is the highest.
In this section three different patterns for the recognition of internal partial discharges at a dc voltage containing a ripple have been reported. The first pattern is characterized by a concentration of discharges, which stretches from the minimum of the voltage towards the maximum of the voltage. The observable discharge magnitudes increase with increasing instantaneous value of the voltage. The second pattern is composed of two concentrations of discharges. Both expand from the left of the virtual zero crossing of the ripple towards the maximum of the voltage and about symmetrically beyond it. One concentration is formed due to large streamer-like discharges and is in the range of nC. The second concentration contains both streamer-like and Townsend-like discharges. It is observable in the range below 100 pC. The third pattern is characterized by a shift of the second
pattern towards the virtual zero crossing of the ripple. The highest discharge magnitudes occur during time instances with high rates of voltage changes. From the findings in this Section it can furthermore be concluded that the overvoltage mainly influences the appearance of the observable patterns.

6.3 Summary

In this chapter the influence of a ripple, which is present on a dc voltage that has been obtained by a half-wave rectification has been thoroughly analysed. Up to a ripple of approximately 0.4 % the discharge behaviour is similar to a purely dc voltage. Above this ripple the ac components of the rectified voltage lead to enhanced overvoltage conditions at the void. As a consequence the discharge behaviour is altered, which is reflected in a strong increase in streamer-like discharge activity. Hence, partial discharge tests should be conducted with a maximum ripple of 0.4 %. Additionally, characteristic phase resolved partial discharge patterns have been derived based on the 0.4 % criterion. The outcome of this investigation are three clearly recognizable patterns.
7 Conclusions

It was the aim of this thesis to develop a novel diagnostic method for partial discharges at dc voltages. This method was to be as easy applicable as the well-known ac resolved partial discharge diagnostic method. Therefore, a phase resolved approach has been used for this new dc diagnostic method. Due to the previously assumed lack of a phase angle it is often claimed that a phase resolved measurement cannot be applied to dc partial discharge diagnostics [2]–[4].

One major aspect in connection with the aim of this thesis was to evaluate characteristic patterns for different types of defects while maintaining a general dc-like discharge behaviour. Here, the three typical artificial defects, which represent corona, surface discharges and internal partial discharges have been examined. All test samples have at first been stressed with a constant peak voltage value while the ripple on the dc voltage was varied. Four different quantities have been obtained from recordings of the current measured in series with the test objects. These were the discharge frequency, the average pulse amplitude, the average pulse rise time and the average pulse fall time. Finally, the test samples have been stressed at a fixed ripple to obtain characteristic patterns for each of the defects as well as for the discharge phenomenon.

The specific conclusions, which can be drawn from the formerly described experiments are given in Section 7.1. These conclusions are then extended to provide a more general context of these new outcomes. These general conclusions are drawn in Section 7.2. Finally, some suggestions for future work are discussed in Section 7.3.

7.1 Specific conclusions

It has been demonstrated that a dc voltage, obtained by a half-wave rectification of an ac voltage, contains a ripple, which can be used as a repeating sequence for phase resolved partial discharge diagnostics. Here, two aspects are of equal im-
portance for the applicability of this newly proposed method. The first aspect, is the distinct and generally accepted difference between ac, dc and combined electric fields, which has been discussed in Subsection 1.1.2. Based on this treatise it can be stated that any not perfectly smooth dc voltage, i.e. a dc voltage with harmonics, will lead to a combined electric field. Thus, a discharge behaviour other than at a purely dc voltage could be expected. The half-wave rectification used in this thesis will consequently result in a combined electric field. Dependent on the level of ripple it could act as a dc field, an ac field or completely different. The discharge behaviour of test objects stressed with such an electric field is however unknown. The second aspect is the unknown appearance of the observable phase resolved patterns. It is thus important to analyse the discharge behaviour with respect to the ripple and to obtain characteristic phase resolved patterns. In this thesis both analysis have been performed for three different artificial defects. The defects represent corona discharges, surface discharges and internal partial discharges.

The following conclusions can be drawn with respect to the ripples influence on the discharge behaviour. It has been shown in Subsection 4.1.1 that for negative corona a maximum ripple of 3 % can be tolerated before the discharge behaviour is altered. This 3 % border is caused by the ripples influence on the movement of negative ions and the displacement current. In Subsection 4.2.1 the maximum tolerable ripple for positive corona has been demonstrated to be 2 %. This value is caused by the influence of the displacement current on the discharge behaviour with increasing ripple. It has been shown in Subsection 5.1.1 that negative surface discharges should be tested with a dc voltage which contains a ripple below 0.8 %. This 0.8 % border could be attributed to the polarity reversal of the ac components, which influences the discharge frequency. For partial discharge tests of positive surface discharges a ripple below 0.8 % is recommended according to the results presented in Subsection 5.2.1. Above this value the discharge behaviour is changed due to an increased surface charge accumulation and the polarity reversal of the ac components. Furthermore, it has been demonstrated that if the peak-to-peak voltage of the ripple is equal to the ac inception voltage, then surface discharges ignite at both polarities irrespective of the voltage polarity. Internal partial discharges should be evaluated at a maximum ripple of 0.4 %, as was elaborated in detail in Section 6.1. Above this value increased overvoltages
lead to increased streamer-like discharge activity. The discharge behaviour hence deviates from a dc discharge behaviour. The given tolerable ripple values provide the opportunity to clearly define a border, below which a dc-like discharge behaviour is maintained. It is hence, for the first time possible to conduct tests with a dc voltage that contains a ripple but delivers test results comparable to a purely dc voltage in terms of discharge behaviour.

Based on the described ripple limitations phase resolved partial discharge patterns of the discharge magnitude have been derived. The outcome are patterns for negative corona, positive corona, negative surface discharges, positive surface discharges and internal partial discharges. These patterns have for the first time been reported for a dc voltage that contains a ripple. For negative corona six patterns between corona onset and breakdown have been presented in Subsection 4.1.2 for a ripple between 0.8 % and 1.1 %. Trichel pulses showed a general tendency for the occurrence of higher discharge magnitudes in the vicinity of the maximum of the voltage. Therefore, the pattern appeared with an envelope function that followed the waveform of the voltage. For the description of the discharge processes the definition of the type 1 Trichel pulse and the type 2 Trichel pulse has been introduced. Both, pulse types showed the aforementioned voltage sensitivity. However, at high discharge repetition rates and solely type 1 activity the voltage sensitivity is lost. It has been demonstrated that this leads to a band like appearance of the discharge magnitudes in the phase resolved representation. The inception of the pulseless glow discharge manifests itself in the disappearance of recorded discharge magnitudes at the corresponding phase instances. This is due to the fact that this discharge type cannot be measured by means of the apparent charge method because of its constant current behaviour. Just before breakdown negative streamers formed a pattern, which was again located in the vicinity of the maximum of the voltage. Here, care has to be taken as the strong negative streamers can lead to integration errors and potentially cause the formation of ghost patterns.

For positive corona discharges five different patterns have been reported at a ripple of 0.9 % in Subsection 4.2.2. A general voltage sensitivity of the discharge magnitudes has been observed. It has been shown that burst pulses appear in groups in the small pico coulomb range. Streamer discharges have a much larger magnitude and usually appear in the range of nano coulombs. Their pattern is
characterized by an envelope function that follows the waveform of the voltage. Streamer discharges can be accompanied by burst pulse activity. They can be dependent upon each other or be independent. It has been shown that the pulsating glow discharge is formed due to never ending burst pulse activity. As no visually observe-able border between those discharge types exist a border has been defined with respect to the period of the voltage. The pulsating glow discharge has been defined as burst pulse activity that spans over at least one full period of the fundamental frequency of the rectified ac voltage without streamer activity. The pulsating glow pattern is located just above the background noise as the underlying dc component of this discharge type is again cut-off due to the measuring principle of the apparent charge method. The last pattern that can be observed before the gap breaks down is caused by breakdown streamers, which ignite in the vicinity of the maximum of the voltage.

At a ripple of 0.6 % three characteristic patterns have been reported for negative surface discharges in Subsection 5.1.2. The discharge magnitudes of Townsend-like and streamer-like discharges were generally effected by the level of the voltage. Higher discharge magnitudes can therefore be reported in the vicinity of the maximum of the voltage. At higher electric field stresses the highest discharge magnitudes are shifted towards the zero crossing of the ripple. It has been experimentally confirmed that leader discharges form different concentrations of discharge magnitudes based on their number of consecutive development steps. At positive polarity a ripple of 0.6 % was used to obtain characteristic phase resolved partial discharge patterns. Two different patterns have been observed as was shown in Subsection 5.2.2. The discharge magnitudes are sensitive towards the level of the voltage at field stresses around discharge onset. At higher field stress the highest observe-able discharge magnitudes are shifted towards the zero crossing of the ripple. Further increased field stress leads to the formation of a glow discharge around the point electrode and decreasing discharge magnitudes.

Three patterns for internal partial discharges at a ripple of 0.4 % have been reported in Section 6.2. At onset, the observable discharge magnitudes increase with increasing instantaneous value of the voltage. The pattern is solely formed due to Townsend-like discharge activity. At higher field stress discharge magnitudes of streamer-like and Townsend-like discharge stretch primarily from the zero crossing of the ripple towards the maximum of the voltage. Again, it can be
reported that the discharge magnitudes are sensitive towards the voltage level. Furthermore, larger streamers form a concentration that aligns with the maximum of the voltage. At still higher field stress, the highest discharge magnitudes are shifted towards the zero crossing of the ripple.

Every pattern presented in this thesis has been related to the physical processes involved. Their cause of formation is therefore known. Consequently, every pattern can be physically related to a defect. Therefore, when a partial discharge test is conducted, conclusions on the active discharge mechanism and on the potential defect location involved can be drawn. Each of the reported pattern, for corona, surface discharges and internal discharges, is unique in its appearance. The defect types can therefore, easily be identified and distinguished from each other. Hence, the novel proposed dc diagnostic method is, as was the aim of this thesis, as easy applicable as the well-known ac PRPD method.

### 7.2 General conclusions

In this thesis the general applicability of a phase resolved partial discharge evaluation method for dc PD diagnostic purposes has been successfully demonstrated. It has been argued that every dc voltage contains a ripple irrespective of the rectification scheme used. Even though, the presented patterns have been obtained by a half-wave rectification the method is not limited to this type of rectification. It is moreover applicable to any dc voltage if the synchronisation frequency is properly selected. It has been recommended to either use the base frequency or the strongest occurring harmonic as the synchronisation frequency. Hence, the proposed method can easily be applied to various industrial energy applications. Therefore, the field of dc diagnostics has for the first time a reliable method that has the potential to be as powerful as the ac PRPD method.

All patterns presented in this thesis have been evaluated at very low ripples, and sometimes at the minimum possible ripple, to observe a pattern. Based on publications arising from this work [132], [133] as well as additional test results it can be stated that the bigger the ripple is, the clearer the individual pattern become. Currently, the maximum recommended ripple for dc tests as given in IEC 60060-1 [111] is 3 %. Hence, a margin between the here presented patterns and the recommended value in the IEC standard of 2 % exists. This means
that even in noisy environments, such as substations, visually clearly identifiable patterns should be observe-able. This is due to the fact that the patterns become clearer with a higher ripple.

A maximum tolerable ripple of 3% for negative corona, 2% for positive corona, 0.8% for negative surface discharges, 0.8% for positive surface discharges and 0.4% for internal partial discharges have been derived in this thesis. The elaborated percentages of tolerable ripple per defect type challenge the 3% criterion of IEC 60060-1 [111]. Unfortunately, no justification for this value has been given in the respective standard. The difference in the here obtained values and the respective standard can lead to far-reaching consequences. If for example a partial discharge test is conducted for a spacer used in gas insulated switchgear that contains a production related void different results could be obtained based on the ripple of the dc voltage. A ripple above 0.4% will lead to a behaviour that is not dc-like. A different electric field distribution and consequently another discharge behaviour is the result. Now, two events are possible if the 0.4% criterion is violated. Firstly, discharges might be active, which would not ignite at a lower ripple or vice versa. Secondly, a higher ripple could lead to a change of the active discharge mechanism, which could lead to an accelerated ageing. It is thus recommended that the 3% criterion is carefully re-evaluated for a revised version of IEC 60060 based on the results presented in this thesis. Even more important is the opportunity to add recommended ripple values for dc partial discharge tests to IEC 60270 to extend the existing standard for partial discharge testing.

7.3 Future work

For the first time the general applicability of phase resolved partial discharge diagnostics for dc purposes has been proven in this thesis. However, the process of establishing a new method requires much more testing then can be covered in one thesis. To achieve a more general acceptance and to enhance the reliability of the method three areas might be further investigated.

Area one is related to the dc voltage. In the thesis a half-wave rectification of an ac voltage has been used to obtain the dc voltage. This type of rectification is common for laboratory purposes. It is however not typical for industrial applications e.g. HVDC for energy transmission. Here, six-pulse, twelve-pulse
7 Conclusions

Converters or multi-level inverters are utilized. They all have in common that their strongest harmonic is usually not at 50 Hz, as in the case of a half-wave rectification. It is hence useful to conduct tests with dc voltage sources that are based on other rectification schemes. For this the tests conducted in this thesis could be exactly repeated for each rectification method. However, if a suitable synchronisation frequency is used, then results comparable to those presented in this thesis should be expected. This has partially been argued in Subsection 3.2.

Area two is related to the test objects. When a new test method is evaluated it is a typical procedure to conduct tests with known defects. This approach has also been followed in this thesis and hence, only artificial standard defects have been used for the pattern evaluation. As the novel test method is intended to be used for industrial purposes it would be useful to conduct tests on real high voltage components. Cables, capacitors and gas insulated switchgear components are some examples of devices that could be tested. It is recommended to approach these components in two steps. Firstly, tests with artificial defects added to partial discharge free components should be conducted. Secondly, the method should be applied to components with defects due to the manufacturing process.

The third area deals with on-site testing and noise. So far tests have been conducted in an absolutely noise free shielding cabinet. Despite the much higher background noise during an on-site test various other sources of disturbances can be expected to be present. Hence, in a final step the proposed test method should be applied to an on-site test.
References


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List of publications

Journal papers

T. Dezenzo, T. Betz, and A. T. Schwarzbacher, “The different stages of prpd pattern for negative point to plane corona driven by a dc voltage containing a ripple”, *IEEE Transactions on Dielectrics and Electrical Insulation*, vol. 24, no. 1, pp. 47–53, 2017

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**Patents**