Master's thesis

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Department of Electric Power Engineering

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Aging of a high voltage insulation system exposed to AC sinusoidal and fast rise time repetitive pulses

Master's thesis in Energy Use and Energy Planning
Supervisor: Kaveh Niayesh
June 2019

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Kunnskap for en bedre verden

Problem description

The main objective of this master thesis is to compare the aging and breakdown behavior of a high voltage insulation system exposed to AC sinusoidal and fast rise time repetitive pulses. For this purpose, two test setups have been appropriately modified to register breakdown (as an indication for the degradation rate of the insulation system) of the insulation system exposed to AC sinusoidal and fast rise time repetitive pulses.

Tests include ramp to breakdown and time to breakdown (at constant peak voltage). Preliminary detection of partial discharges has been performed either optically using photomultipliers or electrically using Omicron PD detection system.

The test object in this work will be an HVDC insulation paper impregnated in MIDEL 7131 synthetic ester (transformer fluid) and placed between two electrodes submerged in MIDEL. Impact of different parameters of the applied voltage (e.g., amplitude, frequencies/repetition rate) will be studied and statistical analysis of the results will be performed.

Preface

This work studies the aging and breakdown behavior of a high voltage insulation system exposed to AC sinusoidal and fast rise time repetitive pulses. The thesis has been performed at the Department of Electric Power Engineering, NTNU Trondheim.

I would like to thank my supervisor Kaveh Niayesh at NTNU, and Co-supervisor Lars Lundgaard at SINTEF Energy Research, for their guidance and assistance during my master thesis. A big thank has to go to Erlend Tveten at SINTEF Energy Research of precious support and NTNU's mechanical workshop for their help constructing the test objects.

Trondheim, June 10, 2019

Mads Alfer

Summary

The anticipated large-scale integration of renewable energy sources with variable power production calls for the use of switching power supplies and frequency converters with power electronics. The fast rise time repetitive pulses generated from on and off operations, are introducing new stresses to the insulation system and increasing the aging and degradation of the insulation.

In this master thesis, it is shown that fast rise time repetitive bipolar pulses are more harmful to high voltage insulation systems than slow-changing AC sinusoidal waveform. Two systems have been customized and utilized to expose test objects to different waveshapes and to register time and voltage when the insulation fails. Waveshapes exposed the insulation are unipolar positive and negative, bipolar and AC. Tests done are ramp to breakdown (Ramped) and time to breakdown (Aging), and the impact of different parameters of the applied voltage has been studied. For both ramped and aging test, the increase of repetition rate cause breakdown either at a lower voltage or at a shorter time by puncture of the insulation, implying more severe deterioration on the insulation.

One of the most harmful mechanisms for the degradation and breakdown of electrical insulation systems are partial discharges (PD) and to measure PD in electrical insulation systems stressed with fast rise time voltages is challenging. The frequency content of the fast rise time repetitive pulses are different from AC sinusoidal and overlaps the conventional PD measurement techniques, and new techniques are needed. This master thesis includes a review of the different mechanisms causing dielectric breakdown with focus on partial discharge and test techniques for AC sinusoidal and fast rise time repetitive pulses.

Sammendrag

Med den forventede storskala integreringen av fornybare energikilder med variabel kraft produksjon krever bruk av kraftelektronikkomformere. De raskt stigende repeterende pulsene generert fra på og av operasjoner har en forverrende effekt på isolasjonen i form av raskere aldring og ødeleggelse av isolasjonen.

I denne masteroppgaven er det bevist at raskt stigende repeterende bipolare pulser er verre for isolasjonen sammenlignet med sakte endrede sinusbølger. To systemer er brukt for å utsette en test objekt for ulike spenningsformer og for å kunne registrere tid og spenningen når isolasjonen ødelegges. Spenningsformene brukt er unipolar negative og positive, bipolar og sinusbølge. Testene som er utført er tid til gjennomslag og økende spenning til gjennomslag, og virkningen av forskjellige parametere for den påførte spenningen er blitt undersøkt.

En av de mest skadelige mekanismene som fører til nedbrytningen og gjennomslag i elektrisk isolasjon er delutladninger og for å måle de i et elektrisk isolasjonssystem når den er utsatt for raske repeterende pulser er utfordrende. Frekvensinnholdet i de raskt stigende repeterende pulsene er ulik sinusbølger og overlapper frekvensspekteret til det tradisjonelle målesystemet. Nye metoder er nødt til å bli tatt i bruk dersom måling av delutladning ved raske repeterende pulser er ønskelig. Denne masteroppgaven inneholder en gjennomgang av de forskjellige mekanismene som forårsaker dielektrisk nedbrytning med fokus på delutladninger og testteknikker for sinusformet og raskt stigende repeterende pulser.

Contents

List of Abbreviations

AC	Alternating current
BD	Breakdown
DC	Direct current
EMI	Electromagnetic interference
FAT	Factory acceptance tests
GaN	Gallium nitride
HFCT	High frequency current transformer
HVDC	High-voltage direct current
IEC	International Electrotechnical Commission
IGBT	Insulated-gate Bipolar transistor
MOSFET	Metal-oxide-semiconductor field-effect transistor
NTNU	Norwegian University of Science and Technology
PD	Partial discharge
PDEV	Partial discharge extinction voltage
PDIV	Partial discharge inception voltage
PWM	Pulse-width modulation
SD	Standard deviation
SiC	Silicon Carbide
UHF	Ultra high frequency
UV	Ultraviolet
VHF	Very high frequency
WBG	Wide bandgap

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1. Introduction

The anticipated large-scale integration of renewable energy sources with variable power production calls for the use of switching power supplies and frequency converters with power electronics. The fast rise time repetitive pulses used operate at voltages with high switching rates and can create high peak voltages with large, $\frac{dV}{dt}$. Combination of these two factors will trigger partial discharges (PD) and accelerate the aging of the insulation systems. However benefits from power electronics are the possibility of shaping the required voltages, enabling a wider range of energy sources such as renewable energy sources and getting more efficient use of equipment.

Power electronics consist of components with the main purpose of switching "on" or "off" and processing energy, creating a wanted voltage, frequency, and phase. Switching operations generates fast rise time repetitive pulses and increase the degradation of insulation systems due to increased partial discharge [1]. The converters operate by implementing the PWM technique and supply load voltages characterized by square waveform with different widths. When applying PWM, the electrical stresses derived are high slew rate voltages (from two to tens of kV/μs), short pulse duration, high repetition rate (repetition frequency in the range of kHz), and frequency transients (see figure 1.1). These elements have a different influence on the PD mechanisms and insulation degradation compared to the conventional AC sinusoidal [2]. During microsecond switching, these converters may generate generating large $\frac{di}{dt}$ and $\frac{dV}{dt}$ that cause severe electromagnetic interference (EMI) and harmonics [3]. Power electronics are needed for applications in photovoltaic, wind, energy storage, electric vehicle, flexible AC transmissions system, and high voltage DC transmission. Newer generations of power semiconductors are based on wide bandgaps (WBG) materials like SiC and GaN, leading to an increase in the applied voltages, higher frequencies, and higher operating temperatures [4]. Equipment operating with higher frequency as IGBT and MOSFET modules require insulation materials which are partial discharge free or resistant [5].

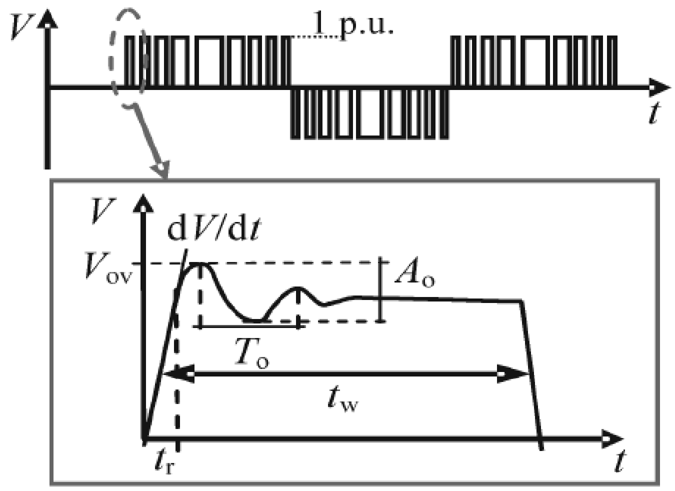

Figure 1.1: PWM sequence with the fast rise time repetitive pulses illustrated [2]

Factory acceptance tests (FAT) of power electronics apply a sinusoidal voltage, unsuited for fast rise time repetitive pulse conditions from switching. Different methods of testing are needed as the new types of voltage stress impacts the performance of the insulation system in the form of reduced partial discharge inception voltage and accelerating aging [4].

It is acknowledged that the use of converters in, for example, controllers for electric motors may be damaging for the insulation due to PD, which is one of the main factors of accelerated insulation degradation. The phenomenon is more harmful for the insulation during PWM voltages compared to traditional AC voltage clarified by the increase of PD pulses [6].

This thesis presents a statistical analysis of breakdown values from AC sinusoidal and fast rise time repetitive pulses to clarify the different stresses on a high voltage insulation system. The different aging effects exposed on the insulation have been studied based on breakdown (BD) values obtained with ramp to breakdown and time to breakdown (at constant peak voltage) to reaffirm the most harmful waveshape [6].

2. Structure of the report

The objective of this master thesis has been a demonstration of increased insulation aging from fast rise time repetitive pulses compared with AC sinusoidal. By customizing and using two test systems, a comparison of the aging and breakdown behavior of an insulation system have been performed.

In chapter 3, the insulation degradation, and breakdown are reviewed with a coherent summary of relevant testing techniques in chapter 4 for the waveshapes used in testing. The two setups and test objects are explained in chapter 5 with a procedure for impregnating the insulation paper.

In chapter 6, the results are displayed from both ramp to breakdown and time to breakdown (Aging) with a discussion regarding the observations. A further discussion section is added within the chapter where the results are compared to theoretical models for insulation degradation.

Conclusion and suggestions for further work are given in chapter 7.

3. Insulation degradation and breakdown

The breakdown processes in solid dielectrics are not as easily understood as for gases, but there are several mechanisms accepted, causing dielectric breakdown in solids:

- Intrinsic breakdown
- Electromechanical breakdown
- Thermal breakdown
- Partial discharges

The intrinsic breakdown is defined in [7] as "the highest breakdown value obtainable after all known secondary effects have been eliminated, and the application of voltage is for short times". The intrinsic breakdown is assumed to be reached when electrons in the insulation gain enough energy from the field to cross a forbidden energy gap from the valence to the conduction band, which takes place after a short time, happens on a time scale of 10^{-8} s.

The electromechanical breakdown happens on a time scale of a few seconds and occurs when the voltage applied across solid insulation is above a certain level. Charges appear at the surface and result in an electrostatic attraction between the surface charges. The solid insulation is then subjected to a compressive force, and under the right circumstances, the specimen collapses.

Thermal breakdown mechanism occurs when the insulation is subjected to an electric field, heat is then generated within the dielectric continuously due to current and polarization. The mechanism happens on a time scale of a few seconds to minutes, and breakdown is achieved when the heat generated exceeds the rate of cooling.

There are types of breakdown which do not conclude with the intrinsic or thermal breakdown but occur after a prolonged time. These breakdowns are due to partial discharge taking place in the solid and is an essential factor to premature insulation failures [7].

IEC 60270 defines partial discharge as: "Localized electrical discharge that only partially bridges the insulation between conductors and which can or cannot occur adjacent to a conductor [8]."

Partial discharges are discharges that affect only a part of the dielectric media and do not immediately lead to an electrical breakdown but deteriorate the insulation over time. Partial discharges in the insulation may be due to the acceleration of electrons, ionization collision, and avalanches. The phenomenon occurs in all insulation types, e.g., gas, liquid or solids. In the case of organic insulation erosion due to PD, frequently and repetitive impulse voltages lead to a significantly reduced lifetime of the insulation material. The phenomenon is a complex stochastic process, and the description of a breakdown in a gas cannot be used in the same matter for solid and liquid since the gas has well-defined properties which are not the case for solid and liquids, but the same principles will apply for all insulation [9].

For PD to appear the voltage must be above the partial discharge inception voltage (PDIV), and there must be either presence of cavities in the insulation, significant aging or electrical field inhomogeneities [5]. Electrodes, especially the cathode, play an essential role in gas discharges by supplying electrons for the initiation, sustaining and completing the discharge.

Electrons are under normal condition prevented from leaving the electrode by electrostatic forces between the electrons and the ions in the lattice and will need external energy to be removed from a Fermi level. This energy is known as the work function and varies for different materials. To supply sufficient energy for electron release, several methods may supply the energy, such as photoelectric emission, electron emission by positive ion, excited atom impact, thermionic emission, and field emission [9].

- Photons whose energy exceed the work function may eject electrons from the cathode surface
- Bombardment by positive or metastable atoms may emit electrons from the metal surface (The electron emission is the principal secondary process in the Townsend mechanism)
- Metal at ambient temperature will not have sufficient thermal energy to leave the surface but increased by 1500-2500 K; the electrons may leave the surface
- A high electrostatic field may draw electrons out of the surface

Liquid and solid insulation consist of different materials, and the chemical properties will vary. They have different material composition, different production conditions, contamination, defects, voids, and aging. The breakdown strength will, in these cases, have strong statistical dispersion, and the breakdown values will vary. In the instance of non-ideal material structures such as impurities, the strength is significantly reduced. This implies the electric strength of solids are determined more by the manufacturing and application of the solid [9]. With solid insulation material, partial discharge is practically always caused by defects within the dielectric in combination with a high electric field. These defects are filled with lower molecular components owing to diffusion processes. Lower electric field strengths may be a result of air-filled cavities with increased stresses due to field displacement. When a discharge occurs, the solid material has not the ability to self-heal and will progressively deteriorate the surface until breakdown. Since solid insulation does not have a self-healing effect, the production quality of solid insulation is essential [9].

3.1 Partial discharge mechanisms

In the following chapter, the description of a dielectric breakdown in gas is described. The same principles are transmittable for both solids and liquids such as Townsend and Streamer, which are applicable for the insulation system used in testing. But due to the different composition, the description of breakdown for these insulation mediums is more difficult to describe.

For all partial discharge, there must be generated a starting electron and have sufficient field strength for the electrons to gain enough energy to cause avalanches.
The two common mechanisms causing PD are:

- Townsend mechanism
- Streamer mechanism

When a high field charges particles, they gain enough energy between collision for ionization on impact with neutral molecules. Electron impact in occurrence with a high field is the most important process leading to the breakdown in gas. Townsend discovered the current would follow the curve as displayed in figure 3.1 when measuring current between two parallel plate electrodes. When voltage is increased beyond the voltage level V_2, the increase in current was described as the ionization of the gas by electron collision. The field increases and the electrons leaving the cathode are accelerating, causing ionization by collision with gas molecules and atoms [9].

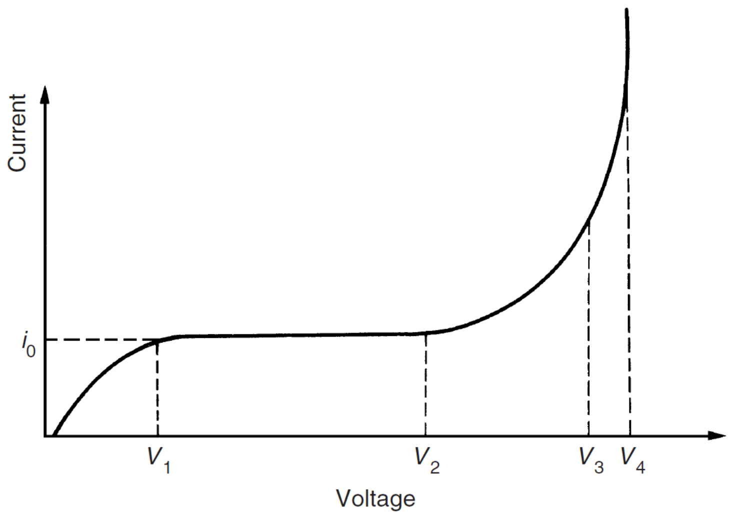

Figure 3.1: Current-Voltage relationship [9]

Townsend describes this by quantity α, Townsend first ionization coefficient and is described in [7] as: “The average number of ionization collisions made by one electron per centimeter drift in the direction of the electric field.” Both Townsend and Streamer mechanisms play the role of describing breakdown but under different conditions. There will be a transition between Townsend to Streamer, such as increased pressure and gap length (d). Townsend mechanism will operate when the necessary gap conditions are, αd in the range of 8-10 and Streamer is transitioned to, when the αd is in range of 18-20 [9].

3.1.1 Townsend mechanism

As the voltage increases, electrode current at the anode will increase according to the equation 3.1 until a point where the dark current I_0 transition to a self-sustaining discharge.

$$I = I_0 \frac{e^{\alpha d}}{1 - \gamma(e^{\alpha d} - 1)} \tag{3.1}$$

α is the Townsend first ionization and d is the distance between the electrodes.
γ is Townsend's second ionization coefficient and are described in [10] as the probability, that one electron is released from the cathode for each generated positive ion.
I_0 is the current resulting from a number of electrons released from the cathode independent of the condition.

Criteria for a breakdown in air due to Townsend mechanism:

$$1 - \gamma(e^{\alpha d} - 1) = 0 \tag{3.2}$$

$$\gamma(e^{\alpha d} - 1) = 1 \tag{3.3}$$

The Townsend mechanism is based on three stages to initiate breakdown:

- The creation of a starting electron
- The multiplication of electrons leading to an avalanche
- Feedback by a process releasing new electrons from the cathode

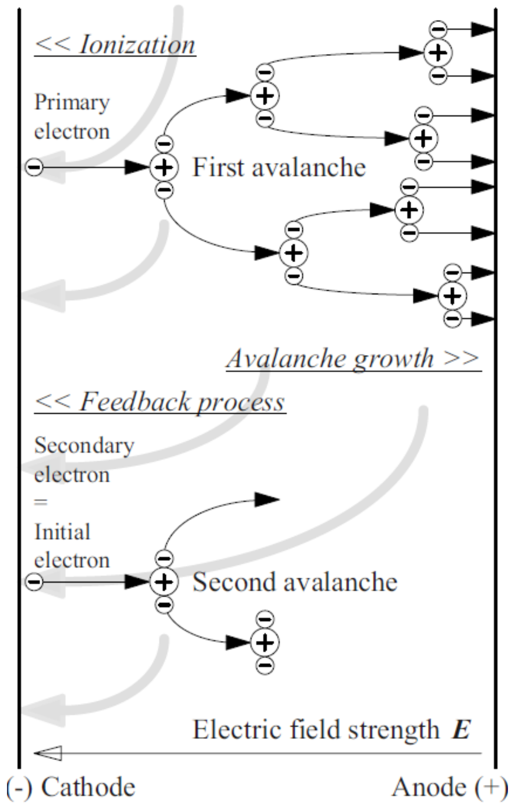

Figure 3.2: Development of avalanches [11]

A breakdown caused by Townsend mechanism will occur if a starting electron appears in a gap between the cathode and anode with a sufficient electric field. This electron will gravitate towards the anode due to the electric field and have an ionization collision. The resulting positive ions from the collision will produce a number of secondary electrons from the cathode surface by bombardment (Feedback process), see figure 3.2. The path of the starting electron will be ended at the anode, but the secondary electron released from the cathode due to the bombardment of positive ions will repeat the same process as the starting electrode. When there is a sufficient number of electrons and positive ions (Plasma) in the gap, there will be a highly conductive path for the current to flow and breakdown is created.

Townsend mechanism is a slower mechanism compared to the Streamer and the time to breakdown happens on a time scale of 10^{-5} seconds. This time lag is the required time for the initiated electron to appear in the gap (Statistical time lag) and the time for the positive charges to cross the gap and hit the cathode to generate a secondary electron (formative time lag) [7, 9]. When there are no initiated start electrons present in the cavity, there will be no ignition. Then it would be a time lag before an electron is present for a discharge to occur. The lack of electrons could be a problem in small cavities, and the sample can be subjected with X-ray to create a starting electron [12].

3.1.2 Streamer mechanism

At the point, the avalanche which was triggered by an initial electron grows up to 10^6 to 10^8 electrons in the gap. The electric field in the space close to the avalanche is influenced by space charges. There will be immobile positive ions remaining in the tail of the avalanche and electrons which are more mobile forming a negative avalanche head, as seen in figure 3.3 [9].

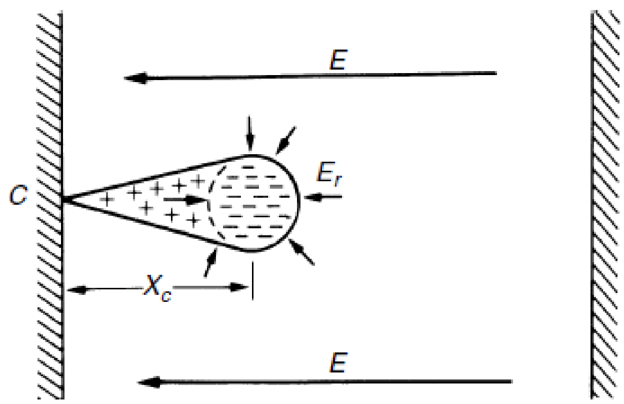

Figure 3.3: Space charge fields close to the avalanche head [9]

When the distance, pressure or the field are increased in the gap, the avalanche becomes unstable at a given length, and the Townsend mechanism criteria are not valid. When αd=20, the electrons reach a critical number of 10^6-10^8 in the avalanche, the transition has begun from Townsend to Streamer mechanism. The principle of Streamer concludes that a complete breakdown can be developed from one single avalanche [10].

The mechanism is based on four stages to initiate breakdown [10]:

- Generation of an avalanche by the initiated electron
- Large local enhancement of the electric field in the space close to the head of the avalanche
- Large amount of photo-ionization of the gas molecules in the head of the avalanche
- New avalanches are amalgamate with original, increasing the size, and when reaching a length equal to the gap, a breakdown is generated

An avalanche ignites at over-voltage, and space charge of more than 10^6-10^8 electrons are developed at the head of the avalanche. Secondary avalanche is generated in the high field near the original one, see figure 3.4.

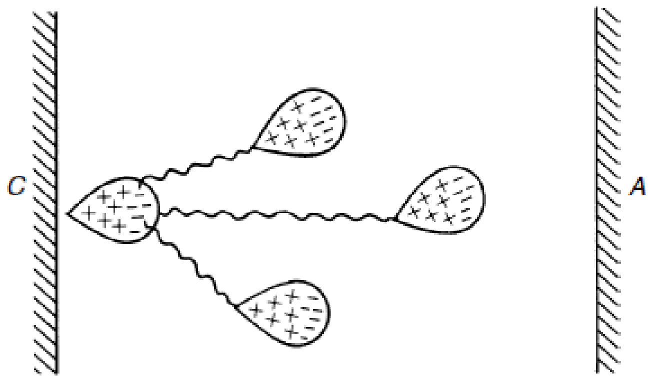

Figure 3.4: Secondary avalanche generated by photoelectrons [9]

This process continues until the gap is covered, and a breakdown is generated in a narrow channel crossing the gap. When this number of electrons is present, it produces extra ionization, and the feedback mechanism is sustained. This results in multiple avalanches which are maintained and builds from the original, and Streamer are generated, which is a space charge dominated discharge [9, 13].

3.2 Types of Partial discharges

Partial discharge is a breakdown phenomenon which partly bridges the distance between electrodes when there is a sufficient local electrical stress concentrated in or on the surface of the insulator [12]. The discharge will appear as a pulse of duration less than 1 μs and is localized in any insulation system as applied in electrical apparatus, components or systems. The partial discharge term consists of several groups [9, 12]:

- Internal discharge
- Surface discharge
- Corona discharge

The discharges are of small magnitude, but they cause deterioration of the insulation and increasing the failure rate of the equipment. The effect on the life of insulation has long been recognized, and every discharge will have a deteriorating effect on the material by the energy impact of high energy electrons or accelerated ions which causes chemical changes in the materials. A perfect insulator will have a uniform electric field, but when a defect is located within the insulator, a high level of electrical stress will be generated in the area of the defect. When the electric field exceeds the breakdown strength of the insulation, partial discharge is initiated. The detection and measurement of partial discharge are based on the energy emitted during a discharge, which are listed in table 3.1 [8, 10, 14, 15]:

Table 3.1: Emitted energy during partial discharge [14]

Electromagnetic	**Acoustic**	**Gases**	**Electric current**
Radio	Audio	Ozone	
Light	Ultrasonic	Nitrous oxides	
Heat			

These physical parameters can be measured with methods mentioned in [5]:

- Traditional measurements according to IEC 60270
- Analyses of PD peak values, time-domain integration
- Impulse voltage test, waveform analysis
- UHF (Electromagnetic wave detection)
- Acoustic PD detection
- Ultrasonic sensors
- Light detection (E.g Photomultiplier)

At the point the discharge is bridging the insulation, the discharge is called a disruptive discharge, and gets different names according to the material used [10].

- "Sparkover" if PD occurs in gaseous or liquid dielectric
- "Flashover" if PD occurs over the surface of a dielectric in a gaseous or liquid medium
- "Puncture" if PD occurs through a solid dielectric

3.2.1 Internal discharges

Internal discharges occur in defects within a solid dielectric, which is usually gas filled. The conditions for internal discharges are caused by aging, poor material, or insufficient production [5]. In the occurrence of an internal discharge, the discharges can be [12]:

- Perpendicular to the field
- Tangential to the field

In all insulation materials, defects are present, and whenever the insulation is connected to a high voltage source, they will work as small capacitors, charging and discharging. Since the breakdown strength in air is smaller than the surrounding insulator, the air will reach a breakdown first. Partial discharge occurs, which generate heat, light, smoke, sound, and electromagnetic radiations. During discharges within the insulation, the defects get eroded and grow bigger. When the size grows the energy dissipated increases accordingly, and gets more conductive and influences the surrounding defects with higher electrical stress. When this possess is repeated throughout the insulation system, there will be enough conductive defects to cause failure and breakdown of the insulation. The occurrence of partial discharge will even occur under normal working conditions, mainly due to transient over-voltages [16].

3.2.2 Surface discharges

Surface discharge appears at the boundary of different insulation materials when the tangential field strength is substantial. The interface could be [12]:

- Gas bounded
- Liquid bounded

There is described in [12] when the surface discharge is observed near the inception voltage, no distinct differences are found compared to internal discharges, but when the voltage is increased beyond the inception voltage, there will be generated streamers at the surface. The deterioration caused by the surface discharges is equal compared with internal discharges described in 3.2.1, but since the area of the surface is more substantial, the cumulative effect is lower.

3.2.3 Corona discharges

Corona discharges occurs in gaseous dielectrics in the presence of inhomogeneous fields e.g sharp metallic points in electrical fields. These discharges may be found at the high-voltage electrode but could occur at the earthed side as well. These discharges are one of the sources of disturbance when measuring partial discharge, and the test area must be kept free of sharp edges or pointy objects if the disturbance is unwanted when the PD is tested [12]. The phenomenon is harmful in case of power equipment and the main unwanted effects are [10]:

- Power loss
- Radio noise
- Ozone production
- Audible noise

3.3 Effect of partial discharge on insulation

By developing high power electrical components, improvement of the insulation system regarding electric, thermal, chemical, and mechanical stresses are essential [5]. The conventional standards for testing high voltage equipment does not consider stresses corresponding from the fast rise time repetitive pulses and equipment which has succeeded the conventional tests may fail under the new type of stress. Exposing the insulation for fast rise time repetitive pulses, the peak voltage may initiate partial discharge faster and cause thermal problems. The dielectric heating increases due to the high-frequency content, even when applying voltages below partial discharge inception voltage (PDIV). Voltages with high frequencies will have an aging effect on the insulation system called intrinsic aging but cause minor effect compared to PD [1].

Voltages over PDIV will cause almost continuously PD activity during fast rise time repetitive pulses and an example in [1] mentioned square wave with a repetition frequency of 10 kHz would have 20 000 PD events per seconds compared to 50 Hz AC with few hundreds of PD events per seconds. The effect of the unipolar or bipolar voltages has been seen to be similar as long as the peak - peak has remained the same [1]. Lifetime and PD magnitude have been investigated in [1], and the results imply when the rise time increases, lifetime decreases, and PD magnitude increases. Factors influencing the aging of insulation from partial discharge are mentioned in [5] as:

- Voltage overshoot from reflection
- Ambient temperature
- Voltage gradient $\frac{dV}{dt}$
- Switching frequency
- Moisture
- Tracking
- UV stress from PD
- Ozone formation (a result of PD)

Partial discharge is a localized ionization of the gas or liquid phase within or surrounding the solid dielectric. The effect is a slow erosion of the material and reduction of breakdown strength in, which eventually results in a breakdown and the three common processes breaking up the organic substances are bombardment by ions and accelerated electrons, chemical reactions, and radiations.

The generated ionized plasma contains electrons, ions, excited molecules, and free radicals, which degrade the insulation. When surface discharges take place, the erosion roughens the surface and slowly penetrates the insulation. The damage to electrical insulation from PD activity is either directly or indirectly a consequence of bombardment by electrons. The ionic bombardment from PD, causes electrons to hit the surface of the void, and organic material decomposes and age. The manufacturing of insulation is difficult to be completely free of gas inclusions, and gas-filled cavities can easily be formed. Which have lower breakdown strength compared to the solid and causes the field intensity to become higher than in the dielectric, reaching the initial breakdown value faster. When a breakdown is achieved in defects, electrons impinging upon the anode will break the chemical bonds of the insulation surface. Similarly, the bombardment of the cathode by positive ions will cause damage to the solid by increasing surface temperature and produce thermal instability. Even when the energy deposition from PD is small. E.g., $< 1\mu$J, some fraction of the electrons produced in the discharge can obtain energies greater than 10eV and can break or disrupt molecular bonds upon impact with the surface. The bond strength are typical $<$10eV. C-H bonds have 3.5eV, C=C have 6.2eV [9, 10, 17, 18, 19].

3.4 Polarity effect

The theory specifies that initiation of PD occurs first in the negative cycles of AC sinusoidal, and may indicate that negative unipolar voltage pulses would cause more rapid erosion of the insulation system and lead to a faster breakdown. When further investigating the different effect negative and positive electrode has when subjecting the test object with positive or negative pulses, an effect called polarity effect come in play. In a non-uniform field, there is a significant difference between the corona inception voltage and the breakdown voltage, which are strongly depended on the polarity of the pulse subjected.

For the negative stressed voltage electrode, the pre-discharge inception voltage is comparatively low, but the breakdown voltage is high. For the positive stressed voltage electrode, the pre-discharge inception voltage is comparatively high, but the breakdown voltage is low (Polarity effect). The polarity effect is caused by the formation of positive space charge close to the point electrode, see figure 3.5.

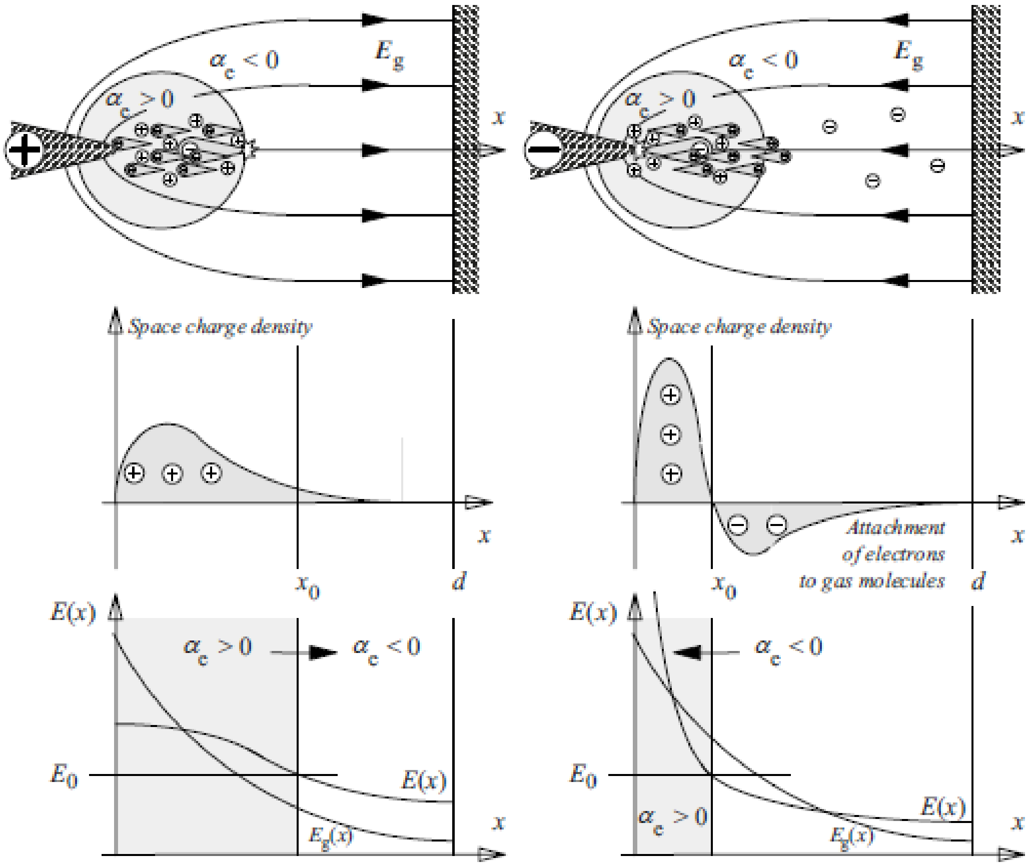

Figure 3.5: Polarity effect for positive and negative electrode [9]

In figure 3.5, I_0 is the ionization boundary, the two top pictures show streamer propagation, the middle is the formation of space charge, and the bottom pictures are the electric strength field curves.

For a positive electrode, the avalanches have to start within the gas volume due to a deficient field strength at the cathode. The first avalanche will be generated if external radiation generates an initial electron in the region with positive ionization coefficients, close to the positive electrode. This avalanche will grow in the direction of the increasing field, towards the positive electrode. If the number of electrons is of sufficient numbers, new avalanches will be initiated within the gas volume by photo-ionization, Streamer mechanism. This first avalanche will result in increased discharge current and glow discharge. The process removes electrons through the positive electrode and creates a positive space charge cloud remaining in front of the positive electrode due to immobile positive ions as shown in the middle left picture in figure 3.5. Resulting in reduced electric field strength in front of the positive electrode and increased electric field strength in the other end of the gap. The field stress enhancement in the low-field region improves the condition for Streamer and breakdown.

For a negative electrode, an initial electron has to be provided on a small surface on the negative electrode, in figure 3.5, the point electrode. This may result in long discharge delay and is called statistical time lag (time to a free electron is available). As the inception voltage is reached, corona impulses may occur, and the initiated streamers propagate into the low field region. When the ionization boundary is crossed, the number of electrons in the avalanche is reduced by attachment to electron-affine gas molecules, and a negative space charge is generated in the low field region. The ionization boundary is shifted towards the negative electrode, and streamer propagation into the low field region and breakdown are postponed.

It states that breakdown voltage is higher for negative compared to positive due to polarity effect. The positive electrode will have a lower breakdown voltage compared to negative since the starting condition of an avalanche is better for the positive, and it can be expected that breakdown will occur first in a positive period for AC sinusoidal [9].

3.5 Stochastic phenomenon

When similar tests are performed at the same voltage level for either AC sinusoidal or fast rise time repetitive pulses. No specific time to breakdown would be observed, but instead, each test would be found to have its own specific time, scattered over a wide range.

As the breakdown is stochastic, it is impossible to predict either the voltage or time to breakdown. Doing a breakdown test with increasing voltage, breakdown at the same voltage level is most certainly not happening. The variation in breakdown strength is said to be stochastic for testing identical samples, and statistical methods are needed as Weibull distribution, average, and standard deviation (SD) to display the result in a simple manner.

To observe the different behavior of high voltage insulation system exposed to AC sinusoidal and fast rise time repetitive pulses, two test setups will be presented in chapter 5. These are both modified to ensure automatic shutdown due to BD and will display time to BD with the related voltage as an indication of the degradation rate in the insulation system. Tests will reaffirm which voltage waveform has the most harmful impact on the insulation.

4. Testing techniques

Fabrication testing of electrical components usually includes PD testing, as part of a final test procedure. Today's prevailing test standard utilizes sinusoidal voltage in test procedures, but with the increasing use of switching power supplies and frequency converters, which employs fast rise time repetitive pulses (square wave) (see figure 4.1), different stresses are generated compared to AC sinusoidal and new testing techniques are needed.

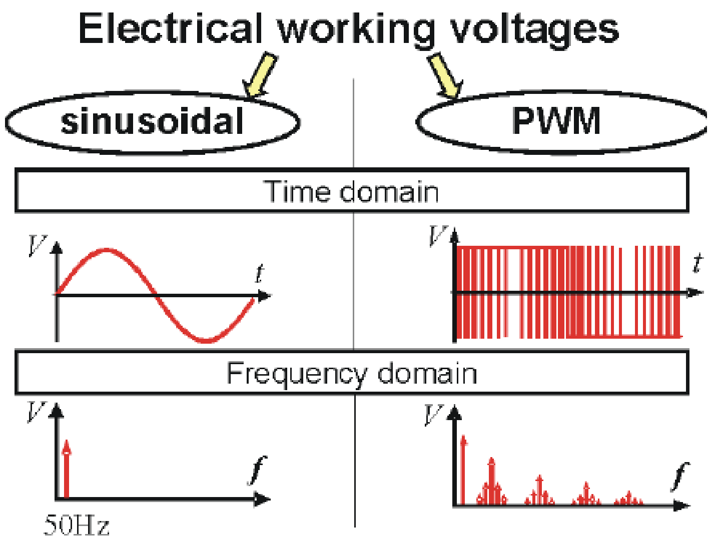

Figure 4.1: Time domain and frequency domain for PWM and sinusoidal [2]

When measuring partial discharges, the apparent charge of partial discharges has become the internationally accepted technical index. It is defined by IEC 60270 as:

> The charge that, if injected within a very short time between the terminals of the test object, would change the voltage across the terminals by an amount equivalent to the PD event [8]

The partial discharge inception voltage (PDIV) and partial discharge extinction voltage (PDEV) are also essential parameters when measuring and analyzing the phenomenon. In practice, inception voltage is when PD activity starts, and extinction voltage is when PD stops [5]. When measuring PD during tests, there are several factors influencing the results [20]:

- Humidity
- Temperature
- Atmospheric pressure
- Type of environment gas
- Degree of contamination of the test object

In the event of pulse-width modulation, fast rise time repetitive pulses are applied in the system, and frequency content from these pulses are different from AC sinusoidal and will overlap the frequency spectrum conventional PD measurements operates in, as shown in figure 4.2 [2].

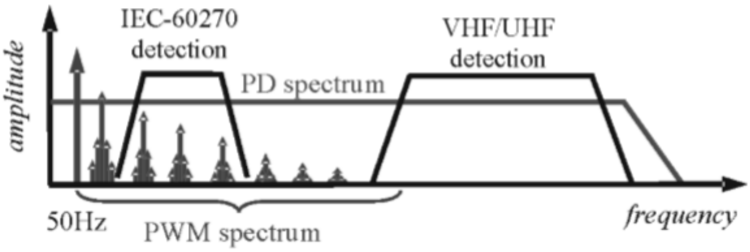

Figure 4.2: Illustration of partial discharge frequency spectrum overlapping with the PWM and detection spectrum [2]

To be able to detect or measure fast rise time repetitive pulses, new methods must be implemented. There is mentioned in [5] that PD detectors should be operating in the VHF/UHF range and for this purpose, non-inductive resistors, capacitive detectors, Rogowski coils, and antennas can be utilized. Electrical stresses are characterized differently for the applied voltage forms. Sinusoidal voltages are characterized by the magnitude of voltage, frequency, and the total harmonic distortion coefficient. PWM voltage, on the other hand, is characterized by the magnitude of voltage, the specific shape of the pulses, pulse repetition rate, and the polarity [2]. Due to the significant differences between AC sinusoidal and fast rise time repetitive pulses, test methods should be divided into two groups, testing with AC sinusoidal and fast rise time repetitive pulses.

4.1 Testing for AC sinusoidal

For measurement, when a test object is subjected to AC sinusoidal and DC (figure 4.3) there has been more research compared to fast rise time repetitive pulses. The standard for testing AC up to 400 Hz or DC is IEC 60270 [8], and for better understanding the standard, CIGRÉ has published a guide: Guide for partial discharge measurements in compliance to IEC 60270 [21].

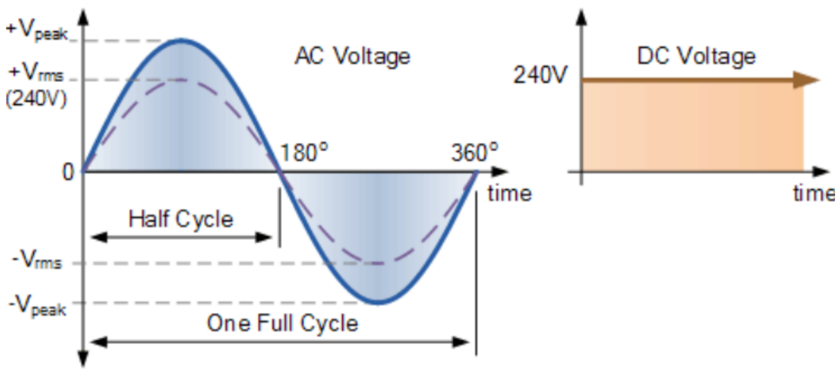

Figure 4.3: Illustration of AC and DC [22]

The main topic in the standard is the measurement using decoupling capacitors in shunt with the test object and an impedance. This enables partial discharge measurement when there is a voltage drop in the test object corresponding from a discharge. Testing with sinusoidal voltages the measurement of the apparent charge is done with these basic test circuits, either with the coupling device in series with the test object (figure 4.5) or in series with the coupling capacitor (figure 4.4). In the figures, C_k is the coupling capacitor, C_a is the test object, and CD is the coupling device connected to a measurement interface.

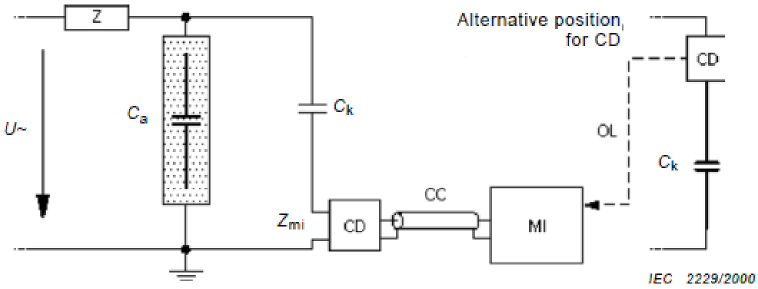

Figure 4.4: Coupling device in series with the coupling capacitor [8]

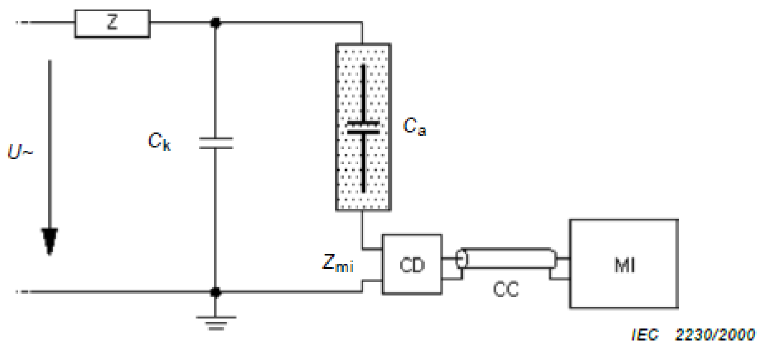

Figure 4.5: Coupling device in series with the test object [8]

4.2 Testing for fast rise time repetitive pulses

The International Electrotechnical Commission has produced a standard, “Electrical measurement of partial discharges under short rise time and repetitive voltage impulses”, IEC 61934 [20]. IEC 60270 [8] describes measurement for DC or AC up to 400 Hz, but testing methods have to be modified to avoid the induced current of the exciting impulse voltage when subjecting the test object with fast rise time repetitive pulses. The motivation for a new standard is the problem with overlapping frequency content between the PWM spectrum and PD spectrum when the object is subjected to fast rise time repetitive pulses. Conventional measurements techniques which operate within the PWM spectrum becomes difficult, and a new approach is needed.

In the standard IEC 61934 for measuring PD, when the test object is subjected to fast rise time repetitive pulses, electrical measurement is done with these methods [20]:

- Coupling capacitor with filter
- High frequency current transformer (HFCT)
- Electrical couplers

4.2.1 Coupling capacitor with filter

A coupling capacitor quite similar to the conventional testing circuit can be used. When measuring with a coupling capacitor (see figure 4.6), the capacitors voltage rating must exceed the applied voltage. The measuring capacitor is shunted with a filter, either with passive or active filter technology for suppressing the impulse voltage to a lower magnitude than the PD pulse.

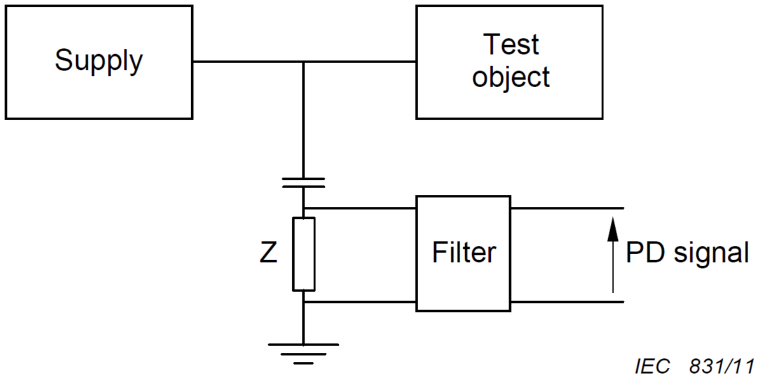

Figure 4.6: Coupling capacitor with filter [20]

4.2.2 High frequency current transformer (HFCT)

High-frequency current transformer, in combination with a filter, could be used as a detection method for partial discharge pulses. Either connected between the power supply and test object (figure 4.7) or between the test object and earth [20]. When used between the supply and test object, the insulation must be sufficient to withstand breakdown. If connected between the test object and ground, the insulation does not need to meet the same requirements due to lower voltages.

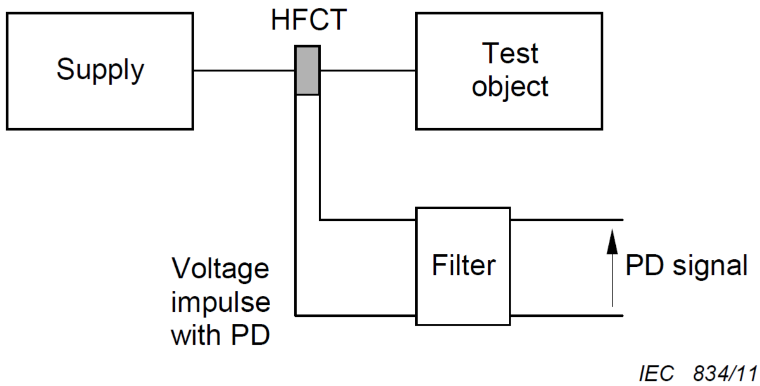

Figure 4.7: High frequency current transformer in shunt [20]

A typical inductive PD coupler is the Rogowski coil, a coil made of several turns. It is an easy way to eliminate the induced voltage in the measuring loop. The output signal will only show when the current is changing. The behavior of the inductive PD coupler is equivalent to a high pass filter since a DC current component will not be induced in the coil [23].

4.2.3 Electrical couplers

During a partial discharge, electromagnetic radiation waves (Radio) are emitted and may cover a range between 1kHz to several 100kHz. With the use of antennas as electrical couplers, an immunity against electromagnetic interference and detection of radiated electromagnetic pulses is achieved, as shown in figure 4.8 [20].

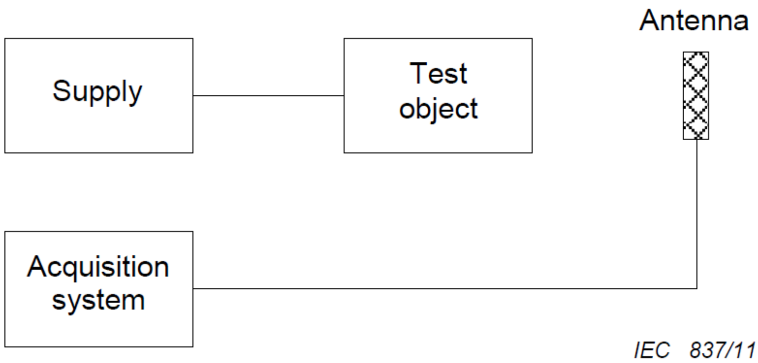

Figure 4.8: Antenna located nearby the test object [20]

5. Measurement setup Experiment

In the present work, a model high voltage insulation system has been stressed with two different voltage waveshapes, AC sinusoidal and fast rise time repetitive pulses. Obtaining breakdown with tests consisting of ramp to breakdown (Ramped) and time to breakdown (Aging, at constant peak voltage). Two systems have been appropriately modified, dedicated to evaluating the effect on an insulation system for AC sinusoidal and fast rise time repetitive pulses.

The object of this thesis is not to measure PD activity, but register the effect on the insulation. For preliminary detection of PD activity, both systems are attached to a PD detection system. In the fast rise time repetitive pulse setup, a photomultiplier has been utilized to detect PD activity. The AC sinusoidal setup uses Omicron, a commercially available PD detection system.

IEC 62068 mentions simple voltage waveform, both square and triangular can be used for testing simple insulation systems with either bipolar or unipolar voltages [24]. For studying the aging effect by fast rise time repetitive pulses, the test system utilized is designed to produce either unipolar or bipolar square wave voltages up to 500Hz in repetition rate. Tests performed are square waved with a 50% duty cycle and repetition rates ranging from 30Hz to 500Hz. For testing with AC, a pre-developed setup has been further customized for the specific test object used. A detailed overview of these two systems is described in the following chapters.

5.1 Test setup for fast rise time repetitive pulses

To generate fast rise time repetitive pulses, an existing system made by SINTEF has been used. The existing system before the thesis consisted basically of a power source and the capability to control it. The rest has been made for the purpose of subjecting fast rise time repetitive pulses on the test object. The main elements in the setup are listed below and a schematic representation is shown in figure 5.1:

- For generating the fast rise time repetitive pulses, there are two high voltage power supplies utilized, Spellman SL 1200, which are used for the positive and negative voltage output, respectively
- The generated power is charging two capacitor banks and are switched on/off by a high voltage solid-state switch produced by BEHLKE.
- Setting the generated voltage in amplitude and repetition rate, a computer with a LabVIEW program is used
- To triggering the generated voltage at the wanted repetition rate, a pulse generator connected to the computer is utilized, Stanford Model DG535
- For preliminary detection of partial discharge, a photomultiplier is utilized

- A voltage probe is utilized to measure the output voltage and further used in the shutdown mechanism

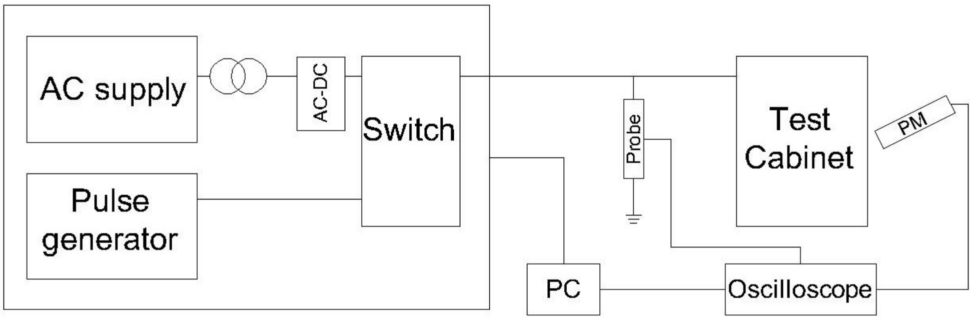

Figure 5.1: Test setup for fast rise time repetitive pulses

5.1.1 LabVIEW program - fast rise time repetitive pulses

It is important to secure the shutdown of the test procedure and after breakdown to exclude fire hazard in the system. A pre-made LabVIEW program has been developed with an automatic safety function. The idea behind the shutdown mechanism is to measure the voltage at the output and to compare the measured voltage with the wanted voltage set in the system. Since there is a difference between measured and wanted voltage during tests, originating possibly from a poorly calibrated voltage probe. It is accepted a 10 % margin between them before a shutdown of the program is initiated. Tests show a 100 % reliable shutdown after implemented the mechanism.

Other features in the LabVIEW program are displayed time to breakdown with the related voltage and the possibility to set voltage, frequency, and a ramped voltage feature, which are used in one of the test procedures. The safety mechanism has an on/off switch, which has to be off from the start since there is a delay before the voltage probe measures the set voltage. At the time the wanted and measured voltage is within 10 %, the safety mechanism can be switched on and will turn the voltage off when a breakdown is registered.

5.2 Test setup for AC

For testing the high voltage insulation system with AC, an existing test setup consisted of a power source (audio amplifier) and two transformers with basic electrical equipment were modified. The further modification of the setup includes a signal generator, oscilloscope, Omicron system and a platform for the test object to be placed upon. A schematic illustration of the circuit is shown in figure 5.2, and the main elements in the setup are:

- For generating the wanted sinusoidal waveform a Tektronix AFG4052C signal generator with a newly developed program in LabVIEW is used
- To amplify the 0-10 peak-peak output from the signal generator an audio amplifier Cerwin-vega cxa-10 is utilized
- Two transformers are used to both ensure isolation and transform the voltage to a higher level

- A coil ensures inductance to the circuit and is made of a long cable wrapped around a reel. The inductance is to phase match the voltage and current signals to minimize the consumption of reactive power in the circuit
- Omicron CPL 512A is connected in series with two coupling capacitors for preliminary detection of partial discharge

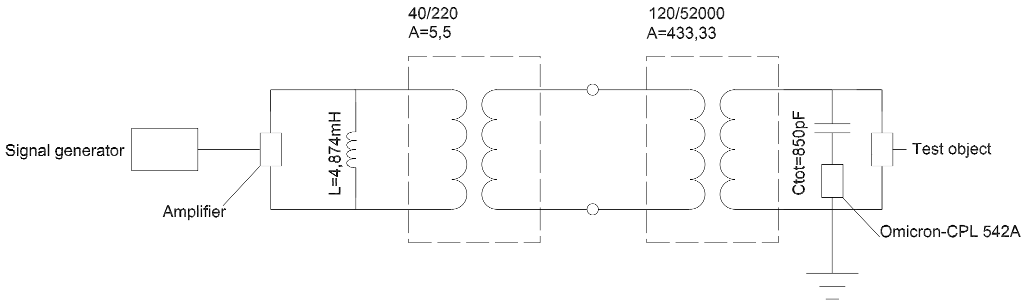

Figure 5.2: Schematics of the test setup for AC sinusoidal

A drawback of the amplifier used is the lack of consistent amplification. During calibration of the amplifier, the test showed non-linear amplification in almost every level, and level that had the most linear amplification was 19, as shown in table 5.1.

Table 5.1: Amplification at level 19

mV	**Amplification at level 19**
50	9800
100	9930
150	10067
200	10125
300	10203
400	10248
500	12830
600	15410

Since level 19 had the most linear amplification, it was used for all testing with AC sinusoidal. Due to the non-linear amplification required a specific input voltage from the signal generator, which was found by testing. It caused the aging test to be more accurate compared with the ramped test since the specific input voltage was set for each voltage level. For testing of a ramped voltage, only an approximation of the wanted voltage level was obtained due to the lack of linear amplification. The results at each kV level are approximate ±100 V from the exact value in ramped testing.

The capacitors used in the test setup are two UHV-12A - Ceramic Disc Capacitor, 1700 pF put in series which gives a total of 850 pF. The impedance was tested in a programmable automatic RCL meter, and the result was L=4.874 mH and R=1.203 Ω.

To calculate the resonance frequency, the components in the circuit needs to be converted to the primary side, see figure 5.3.

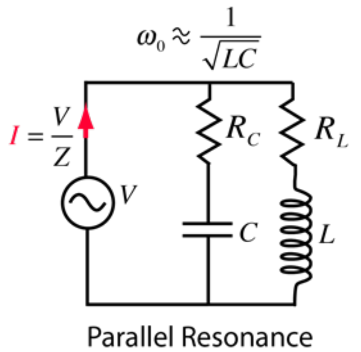

Figure 5.3: Equivalent circuit of the AC setup for resonance calculations [25]

The capacitors are converted to the primary side with the following equation 5.1.

$$C^{‘} = 850 \text{ pF} * 5.5^2 * 433.33^2 = 4.828 \text{ mF} \tag{5.1}$$

The parallel resonance is defined at the frequency at which ωL=$1/\omega C$ as long as the resistance in the circuit is low. At this frequency the current is in phase with the voltage, and resonance frequency for the test setup is elaborated in the following equation 5.2 [25]:

$$\omega\text{L} = \frac{1}{\omega\text{C‘}} \rightarrow \omega_0 = \frac{1}{\sqrt{\text{L*C‘}}} \rightarrow \text{f}_0 = \frac{1}{2 * \pi * \sqrt{\text{L*C‘}}} \approx 30 \text{ Hz} \tag{5.2}$$

5.2.1 LabVIEW program - AC

For the best comparability of breakdown values between AC sinusoidal and fast rise time repetitive pulses, a signal generator is utilized to stimulate a sinusoidal voltage connected to the amplifier. In combination with the signal generator, a LabVIEW program is modified for setting the necessary parameters. The program has features such as setting, ramping, measure current, and display the time at the breakdown. The safety mechanism used in this setup for ensuring shutdown at a breakdown is a current clamp connected to an oscilloscope monitored from the LabVIEW program. The safety feature automatically stops the system when the current is measured above a given level. In the event of a breakdown, a strong current pulse is generated in the system. This pulse is used as a trigger for the shutdown.

5.3 Test object

There has been made two test objects with the specific purpose of testing a high voltage insulation system with either fast rise time repetitive pulses (figure 5.4) or AC sinusoidal (figure 5.5). Both of the test objects are composed of high voltage-graded cable insulation (HVDC) paper (105 μm in thickness), transformer oil (MIDEL 7131) and electrodes which the insulation paper is placed between. The insulating part of the test objects are similar, and tests done are comparable. Both test electrodes were constructed with help from NTNU workshop. For reducing the humidity in the insulation paper and oxygen in the transformer oil (MIDEL), they were treated in a Binder vacuum drying chamber as described below. The procedure for impregnating the insulation paper and assemble the test object:

- The HVDC insulation paper was cut in circles to fit the petri dishes and bottom electrodes.
- The insulation paper was treated in a vacuum chamber for 24 hours at 90°C
- After 24 hours the heated insulation paper were placed in a bowl filled with MIDEL and repeated the heating and vacuum process for 72 hours at 90°C
- The impregnated HVDC insulation paper is then placed centered between the two electrodes and submerged in MIDEL, as illustrated in figure 5.4

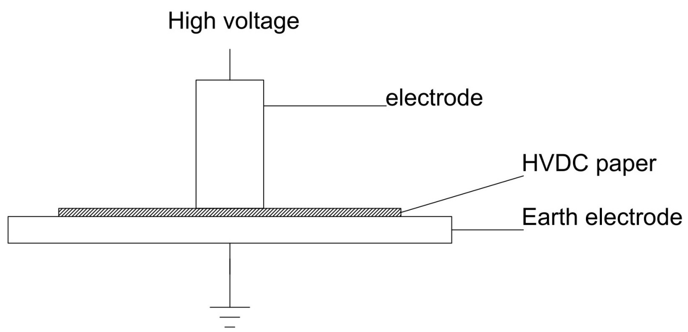

Figure 5.4: Illustration of the test object for fast rise time repetitive pulses

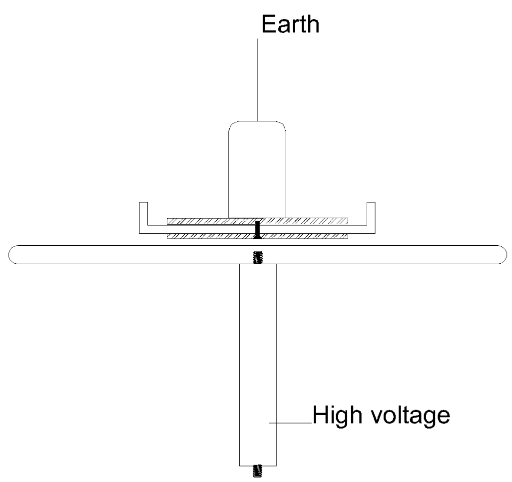

Figure 5.5: Illustration of the test object for AC

The insulation paper was tested in an Oven sample processor by Metrohm to determine the moisture content in the paper after treatment. Three tests were performed: Before dried in the oven, after dried in the oven and after impregnated in oil. The test results indicated a decrease in water content from 5.020% to 0.503%, as shown in table 5.2:

Table 5.2: Moisture content in paper

Name	**Water %**	**Water ppm**
HVDC - before dried	5.020	50211.87
HVDC - after dried	1.187	11540.90
HVDC - after impregnation in oil	0.503	5018.67

5.3.1 Test object for fast rise time repetitive pulses

For the testing with fast rise time repetitive pulses, the test object consisted of two electrodes made of copper, which have 4 mm holes for banana plugs for connection with the earth and power supply. The top electrode is 30x50 mm, and the earth electrode is 90x4 mm, see figure 5.6. The HVDC insulation paper is placed between the electrodes and submerged in MIDEL.

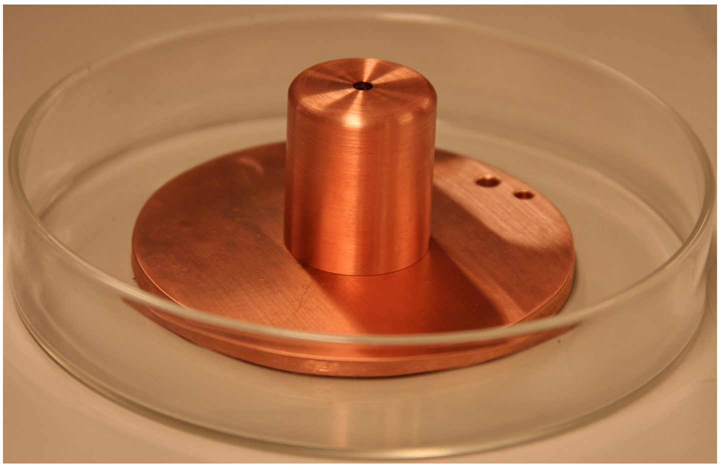

Figure 5.6: Test object for fast rise time repetitive pulses with drilled holes for banana plugs

5.3.2 Test object for AC

The test object for AC is different in design compared with the fast rise time repetitive pulse test object and is shown in figure 5.7. The dimensions of the top electrode are 30x35 mm, and the two bottom electrodes are 63x10 mm. With this design, the bottom electrode consists of two electrodes connected with a screw and two toroidal seals to ensure no leakages. The HVDC insulation paper is placed between the electrodes within the petri dish and submerged in MIDEL.

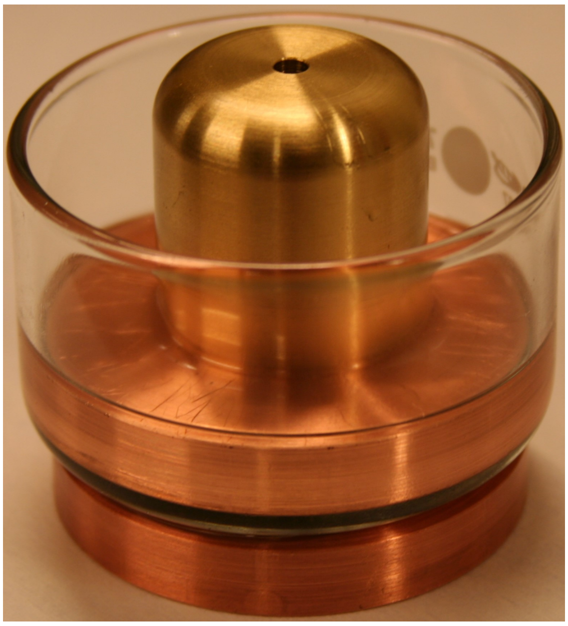

Figure 5.7: Test object for AC testing

When constructing the platform (round electrode) for the test object, the maximum field distribution from the electrode to walls had to be calculated to prevent breakdown, see figure 5.9. The round electrode and wall is equivalent to sphere - plane gap and in the setup, the maximum field distribution needs to be below 3 kV/mm to prevent breakdown in the air. The equation 5.3 calculates an approximately maximum field strength for a sphere - plane gap.

$$E_{max} = 0.9 * \frac{V}{X}\frac{R+X}{R} \tag{5.3}$$

V is the applied voltage
X is the distance between the sphere to the plane
R is the radius of the sphere
To ensure the maximum field strength is equal or below 3 kV/mm the parameters are calculated to be: Radius = 7.5 mm and Distance: 120 mm (electrode to walls)
The maximum applied voltage is then 23.5 kV when $E_{max} \approx$ 3kV/mm [9].

In the long term, the idea is to have more than one test sample placed on the top electrode to do several tests in parallel, as shown in figure 5.8 and 5.9. With the given dish size, it will be possible to do 5 test at once, but in this thesis, only one sample was tested for each run.

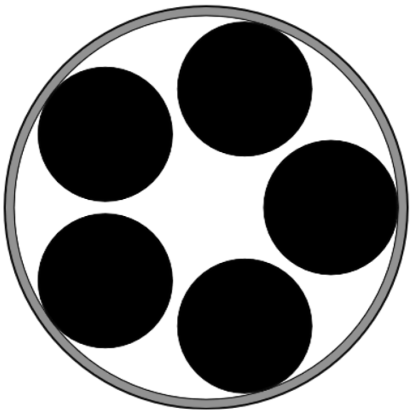

Figure 5.8: Illustration of the test object positions

Figure 5.9: Top electrode connected to the transformer

6. Results and discussion

A study of breakdown tests has been performed with ramp to breakdown (1 kV/min) and time to breakdown at constant peak voltage. A total number of 340 breakdown tests were performed and analyzed. The rise and fall time for bipolar and unipolar pulse was approximately 500 ns. The ramped testing procedure was performed by increasing the voltage by 1 kV per minute, starting from 4 kV peak - peak for bipolar and AC sinusoidal, or zero - peak for unipolar. The voltage was increased until a breakdown in the insulation was achieved, and the breakdown voltage registered. For the aging procedure, a set voltage level remained the same during the test until a BD was achieved, and time to breakdown was registered. The impregnated paper was replaced after each run and to observe the different effects, several voltage levels and different repetition rates/frequencies have been tested and compared. For both of the testing procedures, waveshapes as unipolar negative and positive, bipolar and AC are used, illustrated in figure 6.1. Breakdown values are analyzed in the following sections.

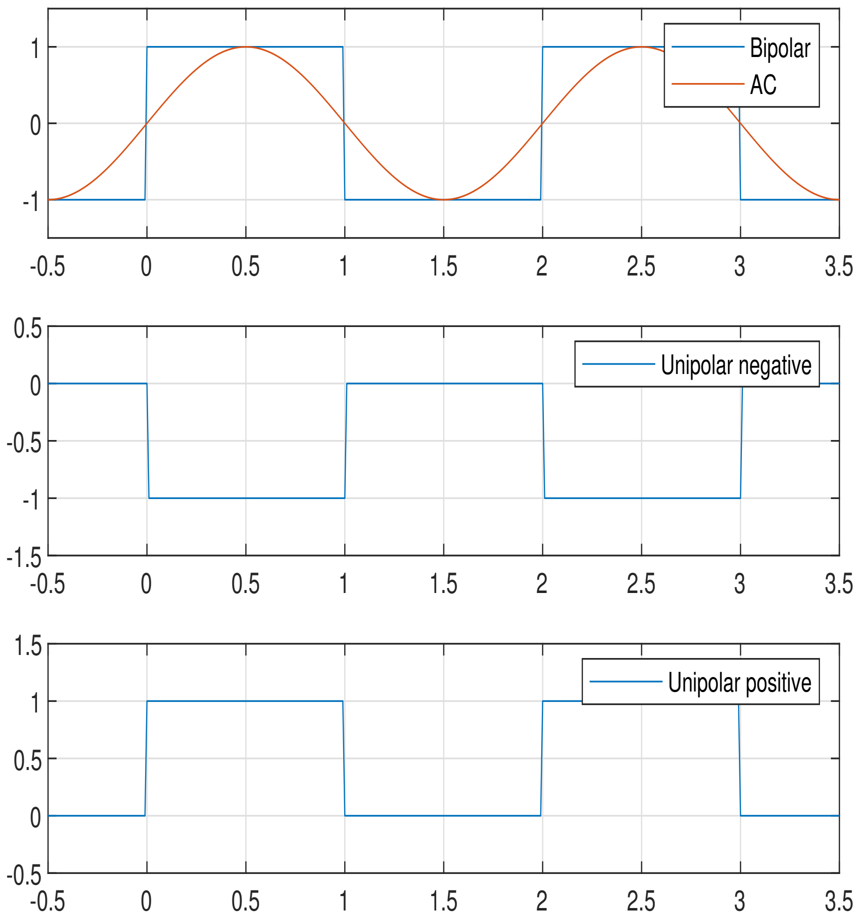

Figure 6.1: Schematic of different wave shapes

6.1 Ramped testing

For this test sequence, a number of 160 specimens were led to failure by increasing the voltage until breakdown with an effective test time of 26 hours. It was tested 10 samples for each waveshape at 30 / 50 / 100 / 200 / 500 Hz in repetition rate/frequency, but AC sinusoidal was only tested at 30 Hz due to the resonance frequency of the circuit. In figure 6.2 and table 6.1, the mean values for each waveform are shown with their specific standard deviation.

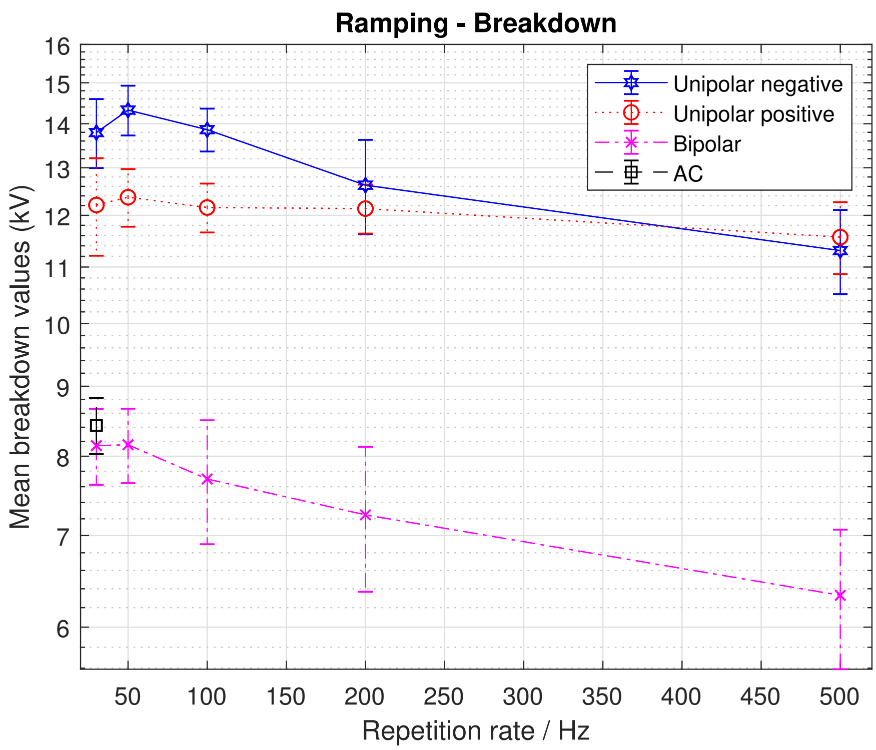

Figure 6.2: Breakdown values from ramp to breakdown, 1 kV/mm

Table 6.1: Breakdown values from ramp to breakdown tests with standard deviation (SD)

Hz	**Bipolar (kV)**	**SD**	**Unipolar Negative (kV)**	**SD**	**Unipolar Positive (kV)**	**SD**	**AC (kV)**	**SD**
30	8.144	0.521	13.795	0.785	12.211	1.036	16.853	0.398
50	8.156	0.512	14.326	0.641	12.372	0.565	-	-
100	7.699	0.799	13.861	0.501	12.159	0.537	-	-
200	7.248	0.878	12.625	1.007	12.137	0.517	-	-
500	6.330	0.740	11.309	0.781	11.568	0.704	-	-

From the results displayed in figure 6.2, the repetition rate for the fast rise time repetitive pulses are influencing the breakdown values. For both the unipolar negative and bipolar test, the increase in repetition rate has a more significant effect on the breakdown value compared to the unipolar positive. Between 200 Hz and 500 Hz, the difference in breakdown values is not as large as for the 30 to 200 Hz. At 500 Hz, the mean value for the negative unipolar pulses is slightly more harmful for the insulation compared to positive pulses. Common for all the waveshapes, is increased repetition rate influences the effect on the insulation in a more harmful way, and the breakdown is obtained by puncture of the insulation.

For the breakdown values from testing, the breakdown voltage levels are referred to as zero - peak. From the results, it can be seen as the pulse is changed from unipolar to bipolar; the zero - peak is reduced significantly. For a repetition rate of 30, the mean value of unipolar negative compared to bipolar is 13.8 kV and 8.14 kV, respectively.

The sequence of changing from a unipolar pulse to bipolar has shown to be more harmful for the insulation. The bipolar pulse introduces alternating polarization within one repetition and increases the number of pulses. As the unipolar only have one positive/negative pulse for each repetition, the bipolar has two. The alternating polarization in the bipolar pulse results in a more harmful effect on the insulation in terms of deterioration.

From test results, the bipolar pulses are worst for the insulation, second is the AC sinusoidal, and the third is the unipolar pulses.

Unfortunately, AC was only tested for 30Hz, and the effect of increased frequencies was not investigated. The hypothesis would suggest that AC would still be less harmful than bipolar pulses as the frequency increases.

6.2 Aging tests

In the aging test sequence, a number of 180 test objects with an effective test time of 20 hours and 37 minutes has been tested with a bipolar pulse, unipolar pulse, and AC. The results are referred to as zero - peak values. Repetition rates tested was 30 Hz, 50 Hz, and 100 Hz for the bipolar pulse and 50 Hz and 100 Hz for the unipolar pulse. For the AC tests, only 30 Hz was tested due to the resonance frequency of the circuit. At each voltage level, 5 samples were tested until the insulation failed, and time to breakdown registered. Impact on the insulation is similar for all of the tests performed; the breakdown is obtained by puncture of the insulation. Tests performed was done to investigate the aging effect on the insulation by comparing waveshapes as:

- Unipolar - negative vs positive (see section 6.2.1)
- Bipolar - different repetition rates (see section 6.2.2)
- Bipolar vs AC (see section 6.2.3)

6.2.1 Aging - Unipolar negative vs positive

To compare the different effect positive and negative unipolar pulses has on the insulation, a number of 100 samples were tested at voltage levels between 10 kV and 14 kV. The results are displayed in figure 6.3 and table 6.2 with the mean value and the range of the 5 tests for each waveform, voltage level and repetition rate.

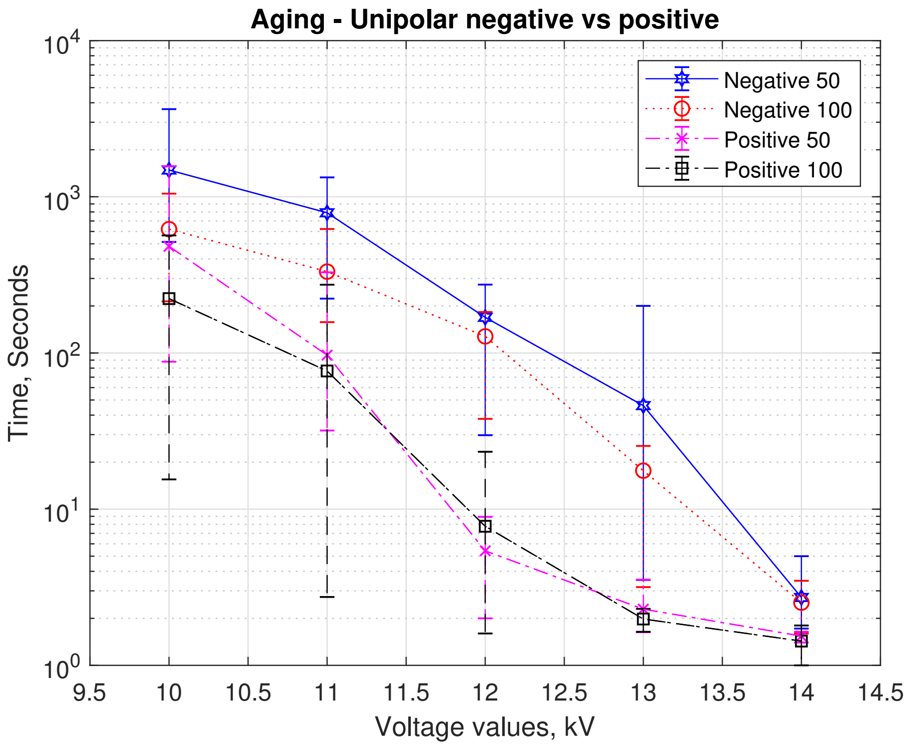

Figure 6.3: Test results from time to breakdown (Aging) - Unipolar - Negative vs Positive

As indicated in figure 6.3, there is a significant difference between positive and negative polarity in aging time. The positive is more harmful on the insulation compared to negative, as theory indicates due to the polarity effect (section 3.4). When increasing the repetition rate from 50 Hz to 100 Hz, the influence of increased repetition rate is more significant for the negative pulse.

Table 6.2: Breakdown values in seconds for unipolar aging with the range of the test

Unipolar aging				
	Negative 50 (s)	**Range**	**Negative 100 (s)**	**Range**
10kV	1483.80	514.00 - 3641.00	620.41	214.04 - 1047.41
11kV	790.15	222.90 - 1331.12	331.69	157.58 - 621.85
12kV	169.06	29.76 - 273.99	127.75	37.85 - 182.94
13kV	46.03	3.52 - 200.26	17.64	3.17 - 25.40
14kV	2.72	1.73 - 5.00	2.52	1.60 - 3.48
	Positive 50 (s)	**Range**	**Positive 100 (s)**	**Range**
10kV	481.94	87.95 - 1571.52	222.95	15.50 - 565.51
11kV	96.90	31.89 - 328.33	76.69	2.74 - 273.60
12kV	5.41	2.00 - 8.94	7.77	1.60 - 23.31
13kV	2.29	1.63 - 3.54	1.98	1.64 - 2.30
14kV	1.54	1.40 - 1.65	1.43	1.00 - 1.80

In table 6.2, the range between the highest and lowest value are displayed, showing when decreasing the voltage level the span increases. The differences in time to breakdown are wide, and the stochastic part of PD takes place. In the higher levels, the time to breakdown is easier to guess compared to when the voltage levels decrease. The theory of polarity effect can describe the clear difference in aging time between positive and negative (section 3.4). The better starting condition of an avalanche for positive pulses is causing an increased deterioration of the insulation compared to negative pulses.

6.2.2 Aging - Bipolar

For the best comparison to AC, bipolar pulses are tested, which include both positive and negative pulse within one repetition. A total of 40 tests was obtained for repetition rate 30 Hz, 50 Hz, and 100 Hz to investigate the effect of increased repetition rate. The aging time for bipolar at repetition rate 30 Hz was not obtained for voltage level 12 kV since the time to breakdown was believed to be in the range of hours as the trend assume. Results from testing are displayed in figure 6.4 and table 6.3 with mean values and the range of the 5 tests for each voltage level and repetition rate.

In the voltage range between 14 kV and 16 kV, the aging time for 50 Hz and 100 Hz in repetition rate remain almost the same. At the same voltage range, it is a large difference in aging time for 30 Hz and 50 Hz in repetition rate.

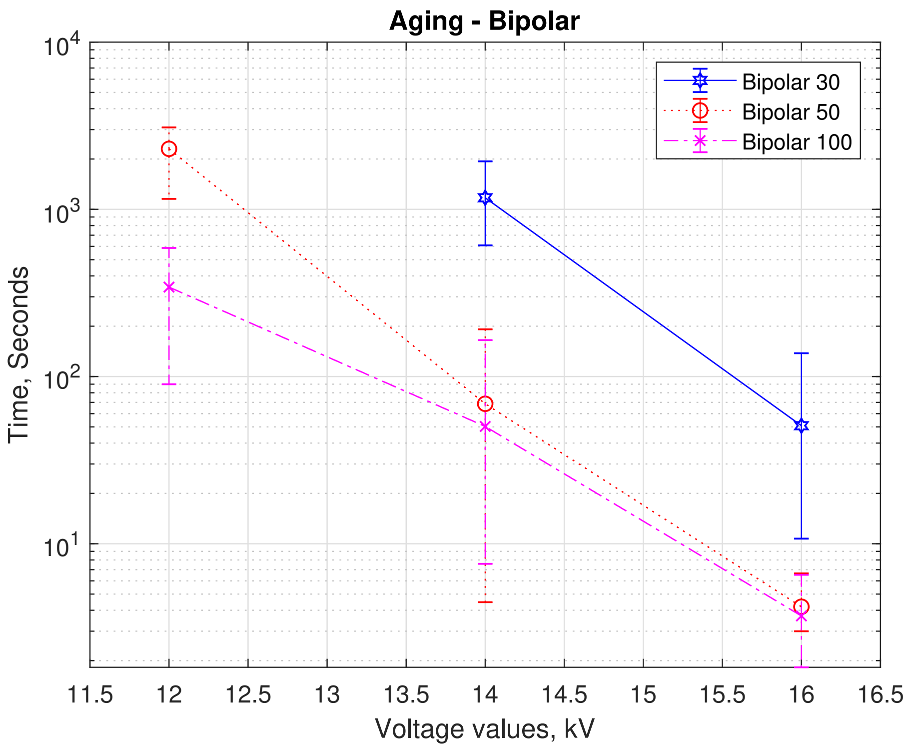

Figure 6.4: Aging - Bipolar - different repetition rates

Table 6.3: Breakdown values in seconds for bipolar aging with the range of the test

Bipolar Aging						
	Bipolar 30 (s)	**Range**	**Bipolar 50 (s)**	**Range**	**Bipolar 100 (s)**	**Range**
12kV	-	-	2300.60	1154.37 - 3090.70	342.70	89.93 - 587.20
14kV	1172.60	609.00 - 1937.00	68.70	4.45 - 191.66	50.30	7.60 - 165.13
16kV	50.91	10.83 - 137.95	4.20	3.00 - 6.65	3.70	1.85 - 5.81

As displayed in table 6.3 the repetition rate 30 Hz, clearly distinguishes from 50 Hz and 100 Hz. At this point, the pulses are not as frequent and do not deteriorate the insulation as fast. In the voltage range between 14 kV and 16 kV, the mean time to breakdown for 50 Hz and 100 Hz are adjacent to each other. In the lower region of the test voltage, the time to breakdown separates, and the effect of increased repetition rate are more distinct. The difference between bipolar 50 Hz and 100 Hz are almost 7 times the aging time at 12 kV. At 14kV, for bipolar 30 Hz and 50 Hz, the differences are even higher, 17 times the time to breakdown.

6.2.3 Aging - Bipolar vs AC

AC sinusoidal and fast rise time repetitive bipolar pulses were tested in voltage intervals between 14 kV - 18 kV at 30 Hz in repetition rate/frequency. The results from the test are displayed in figure 6.5 and table 6.4 with mean values and the range of the 5 test for each voltage level and waveform.

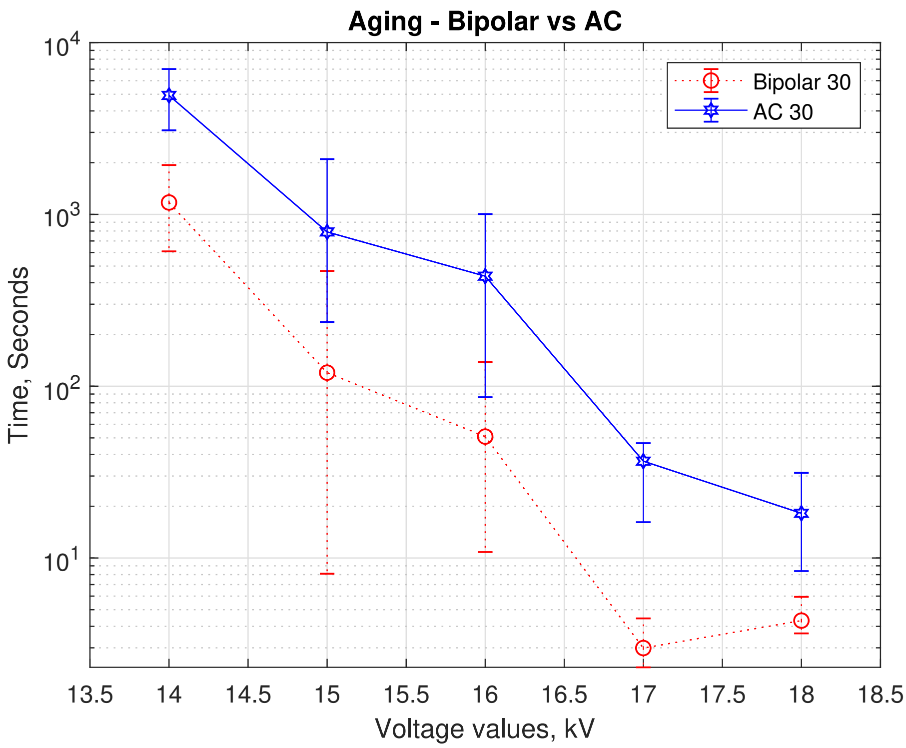

Figure 6.5: Aging - Bipolar vs AC

Table 6.4: Breakdown values in seconds for AC and bipolar with the range of the tests

AC vs Bipolar				
	AC 30 (s)	**Range**	**Bipolar 30 (s)**	**Range**
14kV	4924.1	3084 - 7014.08	1172.6	609 - 1937
15kV	790.2	236.33 - 2097.22	119.9	8.07 - 468.75
16kV	463.8	113.22 - 1031.24	50.9	10.83 - 137.95
17kV	36.6	16.19 - 46.61	3.0	2.3 - 4.45
18kV	18.2	8.45 - 31.33	4.3	2.7 - 5

The hypothesis is that the fast rise time repetitive bipolar pulses would be more harmful and cause a lower breakdown value compared to AC sinusoidal. The results from testing confirm, there is a clear difference between the waveshapes, as shown in figure 6.5 and table 6.4 by the mean time to breakdown and the range of test samples. The time to breakdown for AC starts at 4 times the aging time as bipolar, and as the voltage increases the differences increases accordingly.

For the voltage levels 14 kV, 16 kV and 18 kV, a cumulative Weibull distribution fit is made to display the probability for breakdown for AC sinusoidal and fast rise time repetitive bipolar pulses. For each voltage level, the 5 tests conducted are sorted by time and a distribution fitter in Matlab is used to generate a Weibull distribution, shown in figures 6.6, 6.7 and 6.8.

For voltage level tested, there is a significant difference between sinusoidal stress and fast rise time bipolar pulses in terms of probability to breakdown. Testing shows clear evidence that the fast rise time repetitive bipolar pulses expose the insulation in a more harmful manner compared to the conventional AC sinusoidal on all voltage levels tested.

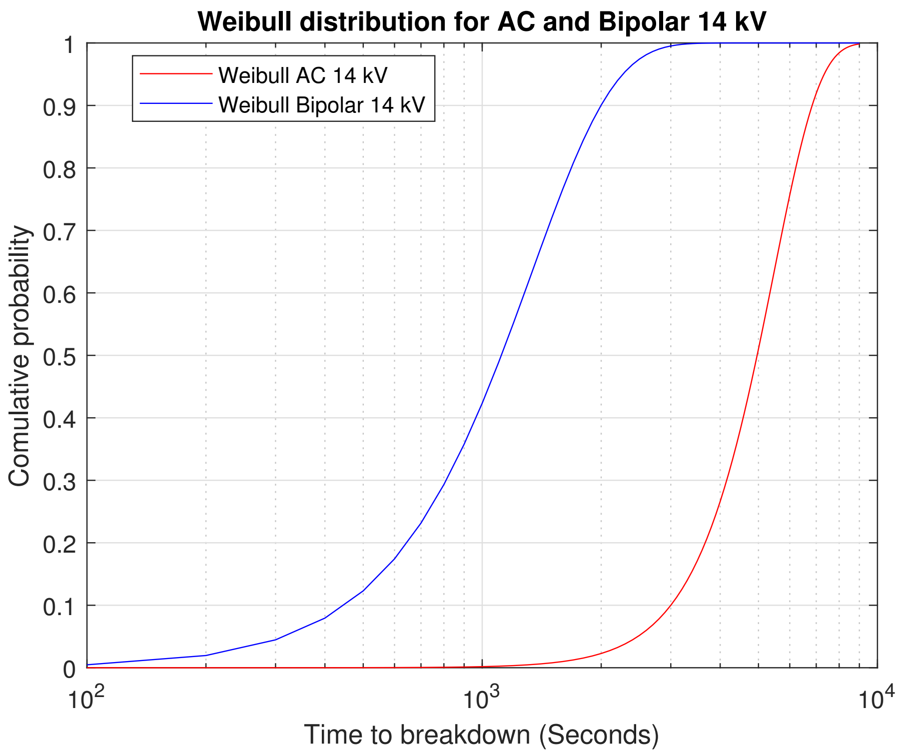

Figure 6.6: Weibull distribution for AC and bipolar 14 kV

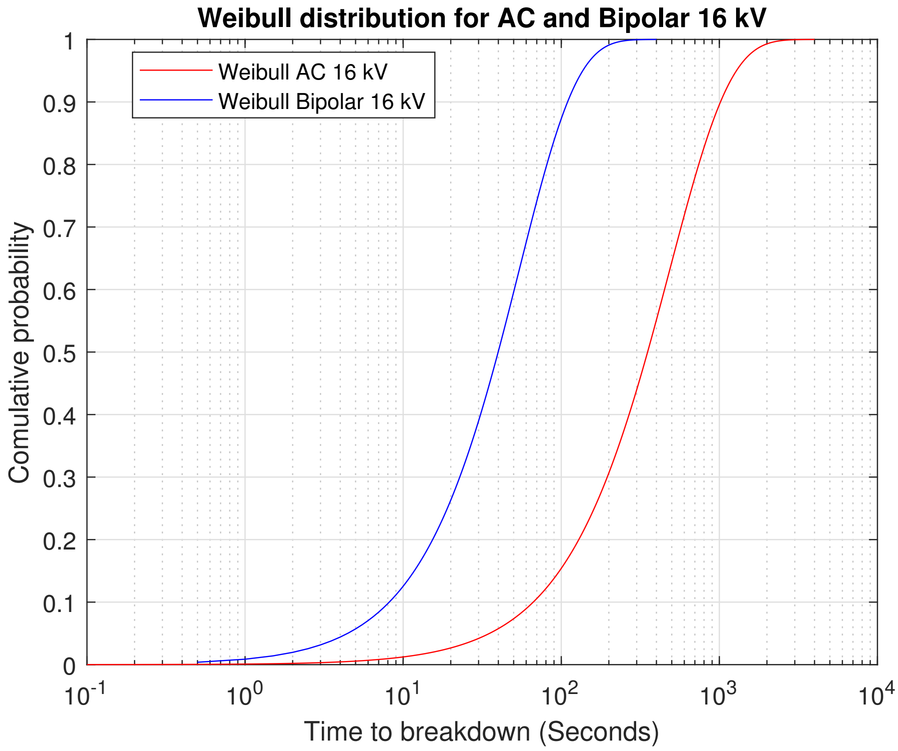

Figure 6.7: Weibull distribution for AC and bipolar 16 kV

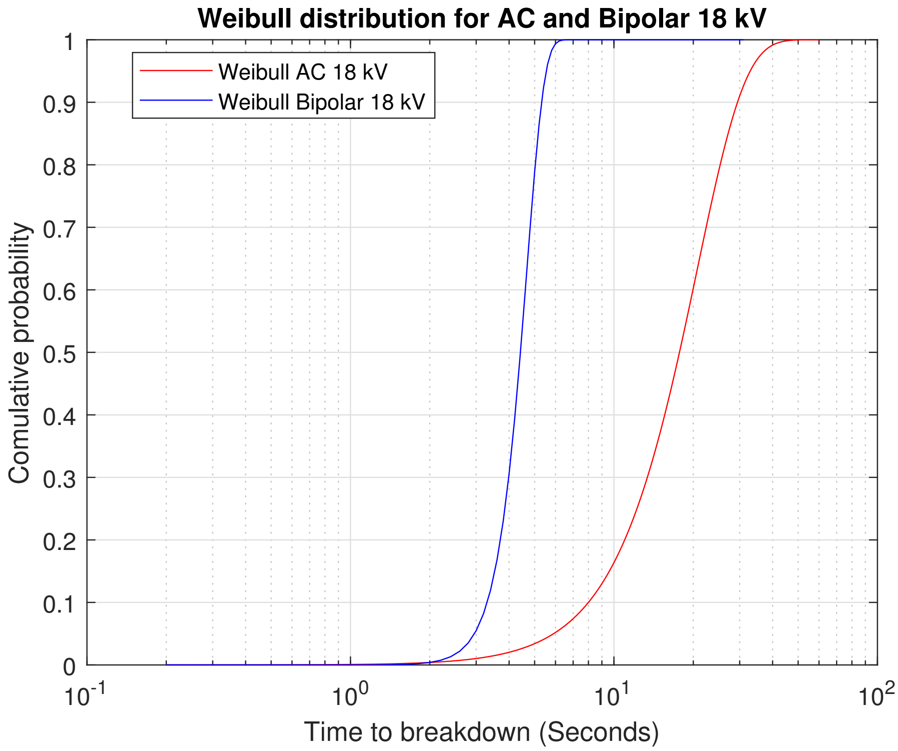

Figure 6.8: Weibull distribution for AC and bipolar 18 kV

6.2.4 Further discussion

The reason there are significant differences between fast rise time repetitive bipolar pulses and AC sinusoidal is the driving force ΔV, a larger rate of rise behind the partial discharge, illustrated in figure 6.9. Consider an equal time lag Δt after a PD for both the square wave and AC sinusoidal before a new PD occurs. At the same time, the differences in ΔV are significant, causing the repetitive pulses to have larger ΔV/Δt. Which is one of the factors influencing the insulation by PD, mentioned in section 3.3.

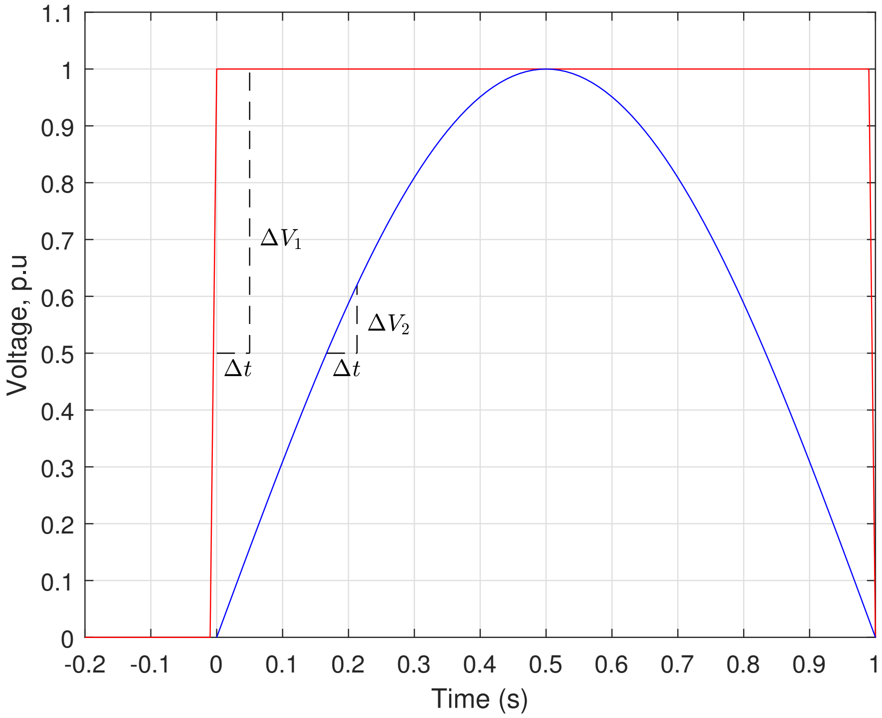

Figure 6.9: Illustration of the differences between square wave and AC

A dielectric material is characterized by its dielectric constant, ε, which relates the electric density D to the electric field, by the relation $D{=}\varepsilon \cdot E$. The part between the edges of the electrode and the surface of the insulation can be seen as a capacitor. When deploying a shifting electric field, there is a time delay departing from polarization, which depends on the dielectric constant. The effect of the dielectric material is an addition to the flux density and will affect the time lag. There are four mechanisms contributing to the polarization produced in a dielectric. Two of them can be seen as more or less momentary polarization: Electronic polarization and ionic polarization. The two last are relaxation mechanisms: Orientation polarization and interfacial polarization, see figure 6.10.

When applying an electric field across the dielectric, the dipoles line up with the field, which takes time depending on the polarization mechanism dominating in the dielectric and the frequency. As mentioned, the two first mechanisms are momentary, called induced dipoles. The last two are time depended on the mechanism and are slow processes, strongly influenced by temperature [10]

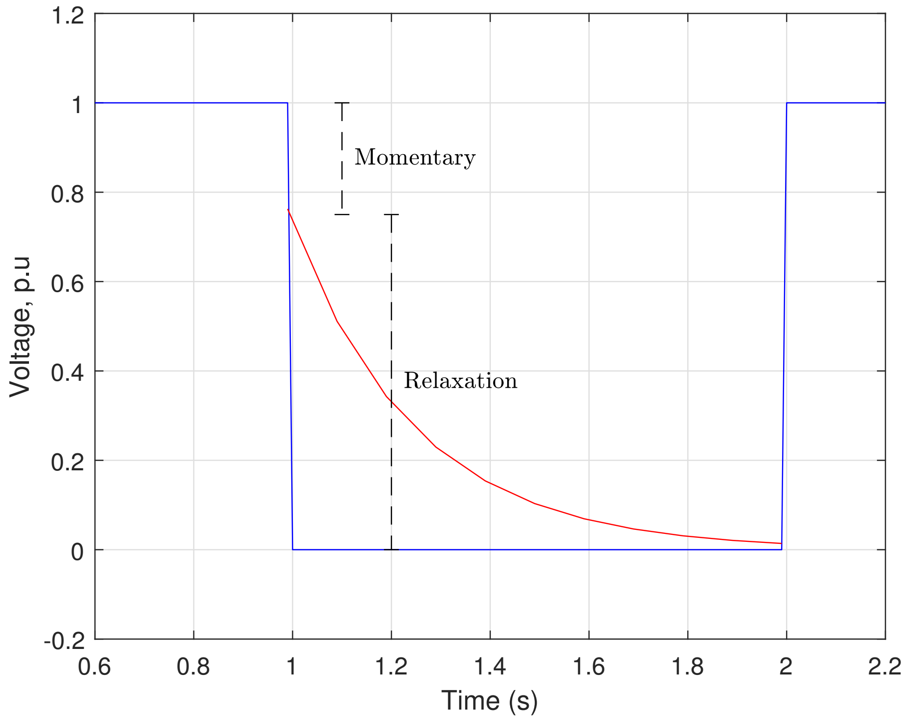

Figure 6.10: Illustration of the delay in applied voltage for fast rise time repetitive pulses

As the voltage of the square wave is decreasing to zero, the momentary mechanism operates fast, and the voltage starts by following the path from the square wave (Blue line, figure 6.10) until the relaxation mechanism starts dominating and causing the voltage curve to differ from the applied voltage shape, introducing a time delay before reaching zero (Red line, figure 6.10).

In the case of the alternating electric field, the dipoles have to keep switching direction as in AC and bipolar waveshapes. At AC in lower frequencies, the dipoles have sufficient time to keep up with the changing electric field, but as it increases the dipoles starts to get out of phase with the applied waveshape.

Consider deploying a unipolar square wave pulse; there will be a time constant before the voltage over the object is zero compared to the applied pulse as mentioned. This time constant can be seen as $\tau = RC$, depending on the material used and temperature. As the repetition rate of the square wave increases, the number of pulses is increased accordingly, and partial discharge has more pulses to be generated. This will possibly cause more damage at the insulation, but since there is a time lag for the voltage over the object to follow the path of the deployed pulse. The voltage may never reach zero voltage before a new pulse is generated if the repetition rate is too high.

Meaning the driving force ΔV for PD will be decreasing in combination with more pulses. If the repetition rate is increased beyond the capability of the voltage subjected has to decrease, it can almost be seen as a DC waveshape. It is causing only the fast polarization mechanism to operate before a new pulse is generated. As seen in the results, the breakdown voltage does not continue to decrease for higher repetition range, supporting the hypothesis that for high repetition rate the voltage may not change fast enough to cause more damage.

The arrangement in the test object used in this thesis, the edges from the electrode is equivalent to a point electrode, and the field enhancement from space-charge at alternating polarity can then be illustrated, as in figure 6.11.

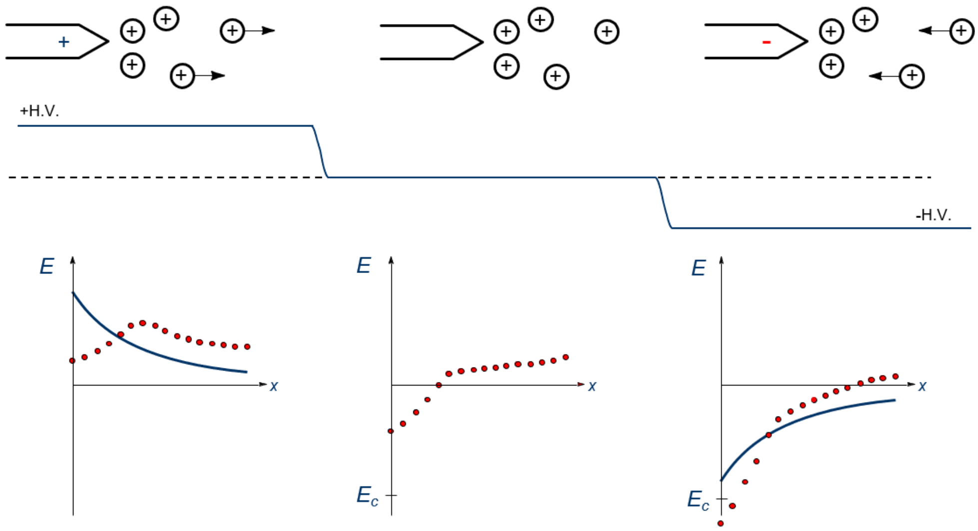

Figure 6.11: Field enhancement from space-charge, alternating polarity [26]

In figure 6.11, the field enhancement from space-charge are illustrated when alternating the polarity. At both positive and negative pulses, the field is highest close to the electrode and decreasing with distance. At the transition of a positive pulse to zero, there is still remaining a field close to the electrode, which will drift away if not a new pulse is generated. The different field enhancement from space-charge at positive and negative pulses gives stronger enhancement from space-charges in positive polarity. This is causing better conditions for breakdown and is causing positive pulses to be more harmful for the insulation compared to negative pulses.

7. Conclusion

Two systems have been used to demonstrate the different effect voltage waveshapes have on a high voltage insulation system, and the results have been analyzed. Partial discharge, the essential factor contributing to premature insulation failures has been reviewed with appropriate test methods for AC sinusoidal and fast rise time repetitive pulses.

For fast rise time repetitive pulses, the positive unipolar pulse has been more harmful for the insulation than the negative pulse, which is justified by theory. Comparison between unipolar, bipolar and AC sinusoidal have been performed from ramped and aging test results. The breakdown values for bipolar are lower than AC sinusoidal and significantly lower than unipolar.

Testing shows clear evidence that the fast rise time repetitive bipolar pulses expose the insulation in a more harmful manner compared to the conventional AC sinusoidal on all voltage levels tested. Similar for both ramped and aging test, the increase of repetition rate cause breakdown either at a lower voltage or at a shorter time by puncture of the insulation, implying more severe deterioration on the insulation. The same effects are evident for time to breakdown, as the voltage level increases the deterioration is more severe.

Unfortunately, the AC sinusoidal were only tested at 30Hz, the effect of increased frequencies could not be investigated, and testing with different frequencies is listed as a suggestion for further work. Partial discharge has only been monitored with appropriate systems to clarify the presence of PD during tests.

The tests have reaffirmed which voltage waveform has the most harmful impact on the insulation, the fast rise time repetitive bipolar pulses.

7.1 Further Work

For further work, the following suggestion is proposed:

- To further investigate the effect on the insulation system, the AC system should be tested with different frequencies
- To get a more linear amplification of the generated signal in the AC sinusoidal system, the amplifier should be replaced
- To investigate partial discharge, the testing techniques listed in this thesis should be used

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Appendices

A. Fast rise time repetitive pulse setup - Pictures

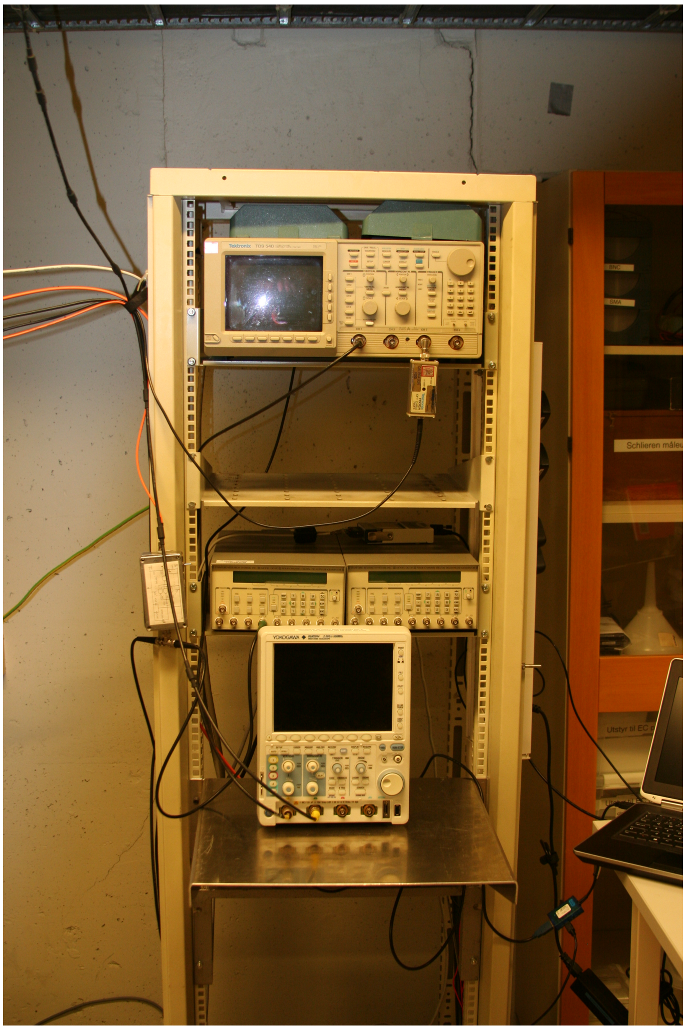

Figure A.1: Measurement and trigger setup for fast rise time repetitive pulses

Figure A.2: Test cabinet 1

Figure A.3: Test cabinet 2

Figure A.4: Test cabinet 3

B. AC sinusoidal setup - Pictures

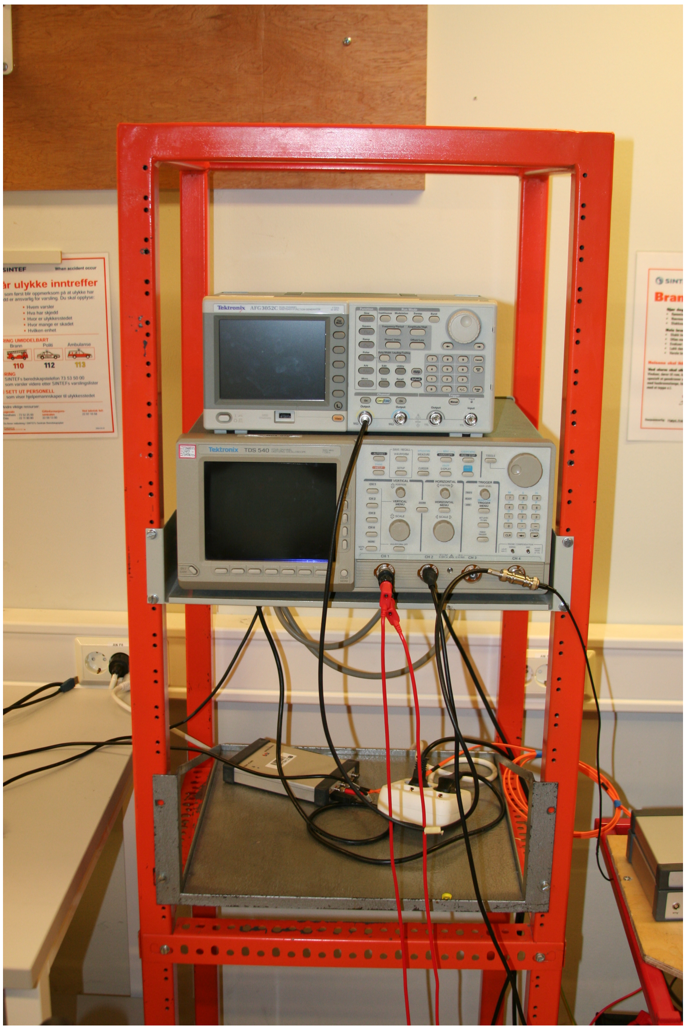

Figure B.1: Measure and signal generator setup for AC sinusoidal

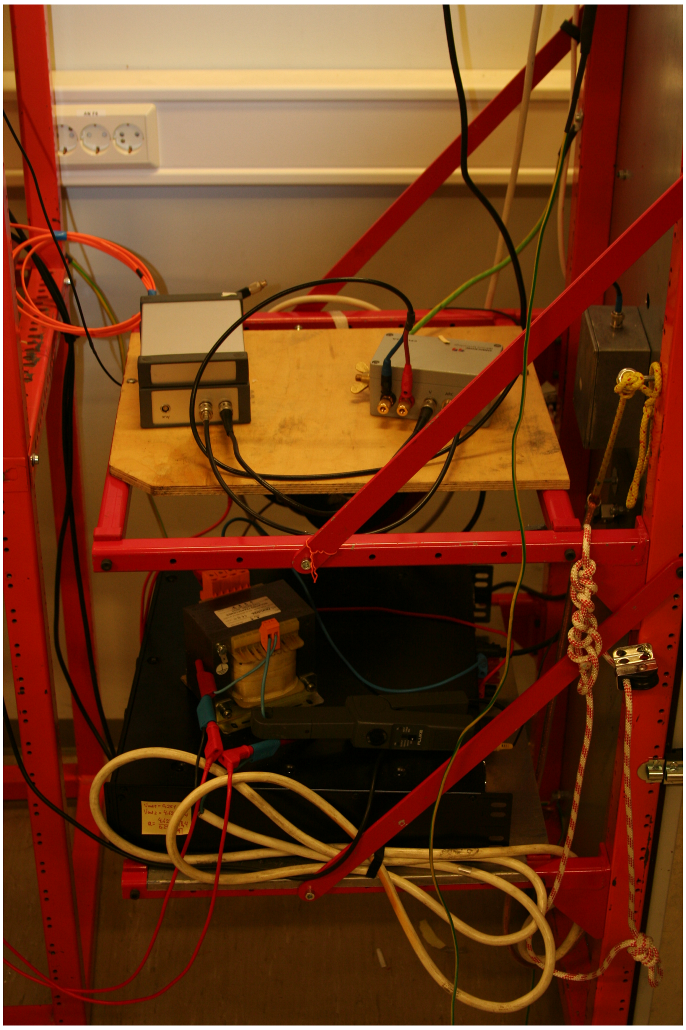

Figure B.2: Test components 1, AC

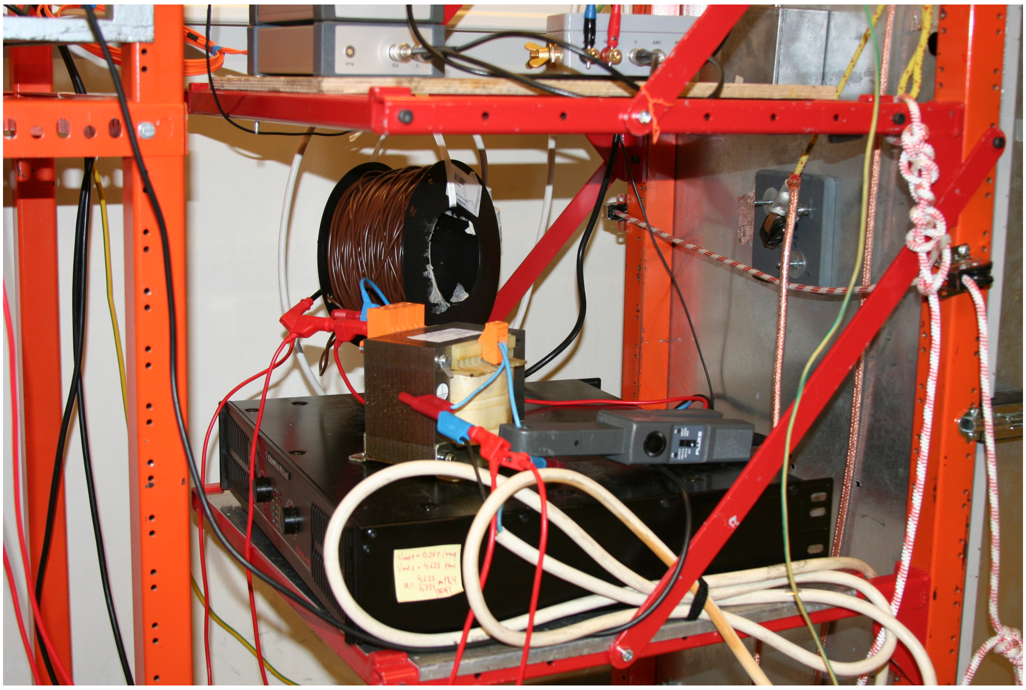

Figure B.3: Test components 2, AC

Figure B.4: Test cabinet 1, AC

Figure B.5: Test cabinet 2, AC

Figure B.6: Test components 3, AC

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