PARTIAL DISCHARGE EVALUATION OF A HIGH VOLTAGE TRANSFORMER

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DECLARATION

I, Isaac Kwabena Kyere declare that this research is my own unaided work, except where specific acknowledgement is made by name, in the form of a reference. It is being submitted for the requirements for the Magister Technologiae: Engineering: Electrical to the Department: Power Engineering at the Vaal University of Technology, Vanderbijlpark. It has not been submitted before for any assessment to any educational institution.

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Isaac Kwabena Kyere

Date: ....

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DEDICATION

This dissertation is dedicated to my late father, Mr Stephen Kodua Tweneboah.

ABSTRACT

This dissertation is devoted to the study of partial discharge evaluation of a high voltage transformer. The 400 V/300 000 V (300 kV) high voltage transformer in the high voltage laboratory was manufactured in 1967. Given the old age of the transformer and the crucial importance of insulation systems, it is vital to assess the condition of its insulation to ensure the effectiveness and the reliability of the transformer as well as the safety of the personnel using it. In order to achieve that, it is important to evaluate the partial discharge in the insulation system as this is the main cause of destruction of insulation.

The phase-resolved partial discharge method was the main method used to perform the partial discharge measurements in this research.

Partial discharge measurements were performed on a faulty 11 kV voltage transformer. Defects were also created in samples of solid insulation at pre-determined locations with different shapes and sizes. The measurements taken on the 11 kV voltage transformer and samples of solid insulation formed a basis to prove the validity of the assessment methods on the 300 kV transformer.

Using the method mentioned above, partial discharges were recorded with respect to the phase of the applied voltage with the aid of a commercial instrument which complies with IEC 60270, (ICM monitor - partial discharge detector from Power Diagnostix Systems GmbH).

The observations from this study have furthered the understanding of partial discharge processes. The patterns recorded were analysed in order to conclude about the condition of the transformer. From the partial discharge pattern, the type and location of partial discharges were concluded. The patterns obtained from the transformer reveal that the device is healthy and can be operated up to 200 kV.

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ABBREVIATIONS AND SYMBOLS

A

AE: Acoustic emission

AC: Alternating current

A: Area between electrodes

C

C: Capacitance

C1: Capacitance of high voltage conductor test layer

C2: Capacitance of test layer flange

C_b and C_{b1}: Capacitances in solid insulation area in series with the void

C_v: The void

C_a and C_{a1}: The rest of the remaining capacitances of the dielectric

Cc: Coupling capacitor

Ck: Capacitance of voltage transformer to earth

D

DDF: Dielectric dissipation factor

DC: Direct current

DGA: Dissolved gas analysis

E

E_v: Electrical field strength across the void

E_{vb}: Breakdown strength of the gas in the void

EMI: Electromagnetic interference

F

FM: Frequency modulation

FDS: Frequency dielectric spectroscopy

H

HF: High frequency

HFCT: High frequency current transformer

HPLC: High performance liquid chromatography

HVT: High voltage transformer

Hz: Hertz

HV: High voltage

I

IEC: International Electrotechnical Commission

ICM: Insulation condition monitoring

K

kV: kilo volt

kA: kilo ampere

kVA: kilo volt ampere

kHz: kilo Hertz

L

LAN: Local area network

LV: Low voltage

LLD: Low-level discriminator

M

MHz: Mega Hertz

MV: Medium voltage

O

OIP: Oil impregnated paper

P

PI: Polarisation index

PD: Partial discharge

PDDS: Partial discharge detection system

pC: Pico coulomb

PCB: Chlorinating polychlorobiphenyls

PC: Personal computer

PDC: Polarisation and depolarisation current

PRPD: Phase resolved partial discharge

R

RBP: Resin bonded paper

RIP: Resin impregnated paper

S

SANS: South African National Standards

T

U

UHF: Ultra high frequency

V

VHF: Very high frequency

V: Voltage

VUT: Vaal University of Technology

VT: Voltage transformer

X

XLPE: Cross-linked polyethylene

Z

Zm: Measuring impedance

$\mathcal{E}_r$: Relative permittivity

$\mathcal{E}_o$: Permittivity of free space (absolute permittivity)

$\mathcal{E}_{rv}$: Relative permittivity of gas in void

CHAPTER ONE: INTRODUCTION AND OVERVIEW

1.1 GENERAL BACKGROUND

A power transformer is an electrical device that transforms energy from one electrical circuit to another by means of magnetic coupling without moving parts. It is often used in high/low voltage and current conversion systems. Lucien Gaulard and John Dixon Gibbs patented the first system using alternating current (AC) in 1882. In 1886, Ganz's engineers (Hungarians) – Karoly Zipenowski, Miska Deri and Otto Blathy patented the first transformer. High voltage power systems were installed throughout the world, based on Zipenowski's transformer invention, where as systems were introduced in the United Kingdom at 132 kV in the 1920s (Ryan 2001).

Partial discharge (PD) has an important effect on the life span of insulation systems of high voltage (HV) equipment. However, it is only in the 1930s, that researchers really paid attention to its degrading effect on HV insulation. "Early studies used ultrasonic detection techniques to assess discharge activities in oil" (Smith 2005). Moreover, from 1960, PD was studied intensively in terms of fundamental physics, its effect on insulating systems and how best to measure and monitor it over time (Smith 2005).

The electrical power department laboratory of the Vaal University of Technology (VUT) has a 300 kV/50 Hz/200 kVA, high voltage transformer (HVT), which has never been assessed for PD. Therefore, there is a need for PD measurement to ascertain proper documentation on a diagnostic method (phase-resolved) that is suitable to assess the condition of the insulation of the transformer. The HVT in VUT's electrical power laboratory is therefore used as the case study for this dissertation work.

In light of the above, it was decided that PD diagnostics would be done to ensure reliable operation of the transformer since it is being used for practical experiments. Since PD diagnostics is a proven method for the effective and non-destructive evaluation of electrical insulation (Power Diagnostix Systems GmbH 2008).

1.2   PURPOSE OF THE STUDY

The purpose of this study is to assess the insulation condition of a high voltage transformer by evaluating its partial discharge. There is the need for a PD measurement in order to assess the condition of the insulation of that transformer. In order to fulfil this aim the transformer in VUTs electrical power laboratory is used as a case study. The study may also support decision-making concerning the transformer's operation under competitive conditions within liberalised energy markets.

1.3   SIGNIFICANCE OF THE STUDY

Transformers are the most important part of the cost structure of a high voltage system. According to Agoris, Meijer, Gulski, Smit and Kanters (2005) the cost of an unexpected failure can be more than the cost of the original transformer installation. Thus, the identification of early warning signs of transformer deterioration could minimise unexpected failures, reduce financial losses and improve the safety in a high-voltage laboratory where students and staff will be conducting HV tests and experiments.

1.4   PROBLEM STATEMENT

Most serious failures of HVT are due to insulation (paper) deterioration leading to a breakdown. The 400 V/300 kV single-phase transformer in the high voltage laboratory of VUT was manufactured in 1967 and the operating conditions prior to 1995 are not known. This is because no formal documentation on operating conditions are available and no maintenance and diagnostic test methods such as PD measurements have been carried out to assess the condition of the insulation of the transformer to ensure its reliability and safety in the laboratory.

1.5   OBJECTIVES OF THE RESEARCH

The main objective of this research is to use a diagnostic method to assess the condition of the insulation of a 300 kV/50 Hz/200 kVA transformer. The diagnostic methods include the:

- characterisation of defects in the transformer insulation system
- analysis of the data obtained from the test

- location of insulation defects as a result of PD

1.6 METHODOLOGY

In order to diagnose the transformer; typical transformer partial discharge defects were made and the corresponding signals characterised.

Partial discharge tests were done on the transformer.

The obtained results were compared with those of the artificially made defects and conclusions drawn out.

1.7 THE SCOPE OF THE RESEARCH

This dissertation assesses the insulation condition of a 300 kV/50 Hz/200 kVA single-phase transformer based on phase-resolved PD measurement through the electrical detection method. The study also explores two methods used to detect the PD signals, namely the use of the coupling capacitor and the inductive coupling through high frequency current transformers (HFCTs). Furthermore, PD patterns are identified.

1.8 RESEARCH OUTPUTS

The outcome of the study gives an indication about the actual insulation status of the transformer and the necessity for maintenance. Some parts of this study have been accepted for presentation at local and international conferences. These papers are:

- Partial Discharge Evaluation of a High Voltage Transformer, presented at the 2013 High Voltage Conference – IDC Technologies on 18-19 September 2013, Midrand, South Africa (Annexure A).

- Partial Discharge Evaluation of a high Voltage Transformer presented at the South African Universities Power Engineering Conference (SAUPEC) on 30-31 January 2014, Durban, South Africa (Annexure B).

- Partial Discharge Pattern Characterization of Different Defects Using 3D Phase Resolved Technique, presented at the International Conference on High

Voltage Engineering and Application on 8-11 September 2014, Poznan, Poland (Annexure C)

1.9   ORGANISATION OF THE DISSERTATION

Chapter 1 introduces the study. It details the motivation to take up this research and presents the identified objectives. The remainder of this dissertation is organised as follows:

Chapter 2 provides a discussion of the literature review covering the field of PDs in high voltage bushings and transformers. This chapter also covers the type of bushings, bushing insulation failures, PD detection methods, transformer insulation and transformer insulation ageing.

Chapter 3 presents the theory of PD. It includes the PD mechanism, PD modelling, and the basic concepts of PD. This chapter also reports on PD in power transformers, PD monitoring in transformers, PD location in transformers, the problem of noise and the signature of PD in electrical insulating materials.

Chapter 4 deals with the experimental procedures of PD measurements. The chapter discusses the measurement of the PDs in samples of solid insulation having known defects which were then used to identify the type of defects and their locations in the insulation of the voltage transformer. The chapter also discusses the results of the phase-resolved PD measurements obtained on the 400 V/300 000 V single-phase transformer.

In Chapter 5, the conclusions are presented. Some future recommendations for the tests that could be carried out in future research are also included in this final chapter.

In the next chapter, the literature review covering the field of PD in high voltage bushings and transformers is presented.

CHAPTER TWO: LITERATURE REVIEW

2.1   INTRODUCTION

This chapter provides the literature review covering the field of PDs in high voltage bushings and transformers. This chapter also covers the type of bushings, bushing insulation failures and transformer insulation ageing.

2.2   HIGH VOLTAGE BUSHINGS

HV bushings carry one or more HV conductors through an earthed barrier such as a metal tank. Transformer bushings are very important for the transformer to operate well on low and high voltages (Septyani, Arifianto & Purnomoadi 2011). Bushings in transformers:

- provide mechanical support for external connections to the transformer and

- Electrical insulation between the conductor and the tank of the transformer (Ryan 2001).

According to Septyani *et al*. (2011), the bushing is an insulator in which the electrical conductor passes through to connect both terminals. The outer part may operate in air, oil or gas, depending on the system configuration (Ryan 2001).

HV bushings form an essential part of power transformers and circuit breakers (Krüger *et al.* 2010). Defective bushings constitute for over 10% of transformer failures, which can result in total destruction of the transformer. According to Schurman (1999), when the HV bushings deteriorate, explosions with considerable force may occur, this will cause extensive damage to nearby equipment or injuries to the personnel. Moreover, most of the avoidable bushing problems are caused by unacceptable water content in the bushing, which enters through leaky gaskets. Flashover may occur as a result of deposits of contamination or moisture on the bushings, which happen in the areas where salt or conducting dust particles are present in the air.

The cracking of the tank, violent blast of the bushing and fire as a result of bushing failure, are caused by the breakdown of the insulation system. The faults that occur on capacitor-type bushings, sometimes lead to a transformer breakdown; whereas, the presence of wetness results in a service-aged bushings explosion (Mehta, Sharma, Chauhan & Agnihotri 2011). Additionally, Septyani *et al.* (2011) detected ageing and water in the insulation of an HV bushing using the dielectric spectroscopy method, by way of conducting tangent delta tests on a sweep frequency, which is the basic idea of this method, providing additional information regarding ageing and water content in the cellulose.

Bhumiwat (2004) and Heizmann, Bräunlich, Aschwanden, Fuhr, Hässig and Müller (2010) used the method of polarisation and depolarisation current (PDC) analysis to evaluate the condition of insulation of the type of condenser bushings, namely, oil impregnated paper (OIP), resin bonded paper (RBP) and resin impregnated paper (RIP). Wańkowicz, Bielecki, Szrot, Subocz and Malewski (2010) assessed the moisture content of a few 110 kV transformer bushings through polarisation and depolarisation current measurement, which the electromagnetic radiation method was used to detect PD on 400 kV bushings between 20 MHz and 50 MHz. The authors report that the breakdown of paper insulation between the adjacent aluminium foils occurs at the sine-voltage peak that may attain 4 kV in 400 kV rated voltage bushing.

Picher and Rajotte (2007) performed on-line diagnostics of bushings through bushing tap current measurement, using the sum current method and the relative measurement method. The sum current method is based on the principle that the vector sum of the bushing insulation current equals zero if the balanced three-phase system voltages and bushings are identical. However, bushings are not identical and system voltages are not balanced in reality. The capacitance and/or power factor changes when one of the bushings deteriorates resulting in the corresponding sum current deviation.

On the other hand, the relative measurement method uses two or more bushings connected on the same electrical phase. The ratio of the amplitudes and the tangent of the phase angle between the fundamental components of the bushing insulation

current are calculated thus, the tangent of the phase angle is sensitive to any change in the power or dissipation factor of one of the bushings (Picher & Rajotte 2007).

2.3 TYPES OF TRANSFORMER BUSHINGS

2.3.1 Solid type bushings

Solid type bushing are made up of a single conductor in the centre and the porcelain insulator at the end, which are used for small distribution transformers as well as circuit switches for power transformers (Ahmed 2011). The conductors of the central parts of the bushings are connected directly to the transformer winding and can be small in diameter, which pass through a bore in the porcelain. The lead and bore of the insulator are concentric and they control the electric stress in the gap, causing it to be uniform at higher voltages.

The insulator between the lead and porcelain is air or mineral oil, depending on the rating and it is used for lower voltages. The electrical-graded mineral oil is also used for higher voltage bushings. Oil is used because of its better coolant and higher dielectric strength than air. Figure 1 illustrates a sketch of solid type bushing.
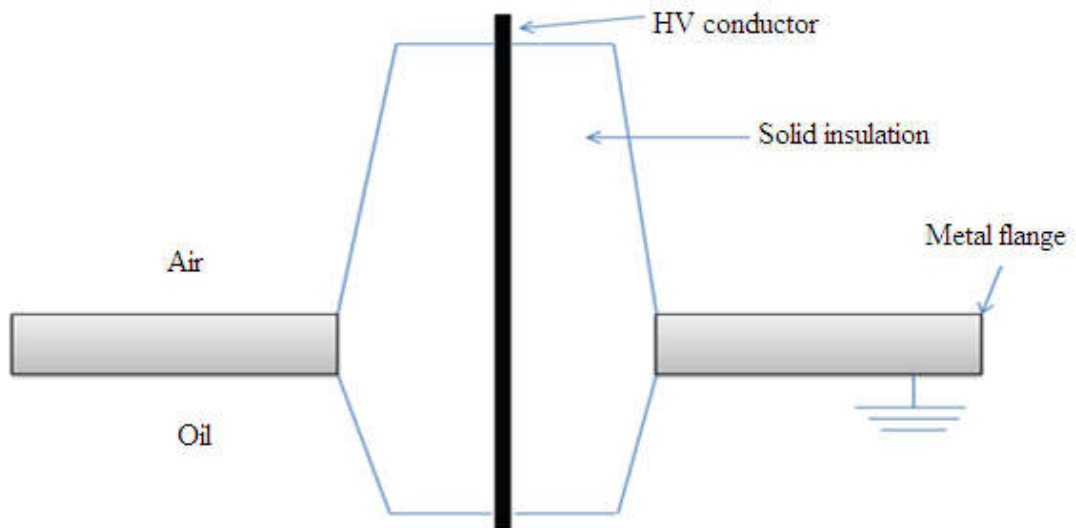
Figure 1: Solid type bushing (Ahmed 2011:8).

The bushing form an integral part of the cast resin winding in the case of dry-type transformers. Porcelain insulated bushings are commonly used for outdoor applications with liquid insulated transformers while cast resin are used for connections inside cable boxes or with separable connectors (Ryan 2001).

2.3.2 Capacitor type bushings

The condenser-type bushing is also known as the capacitance-graded bushing (Ahmed 2011). The author states that the difference between the axial length and the adjacent metallic cylinders is equal to the voltage distribution along the bushing surface. Capacitor-type bushings consist mainly of paper insulations. Figure 2 shows the capacitor type bushing.
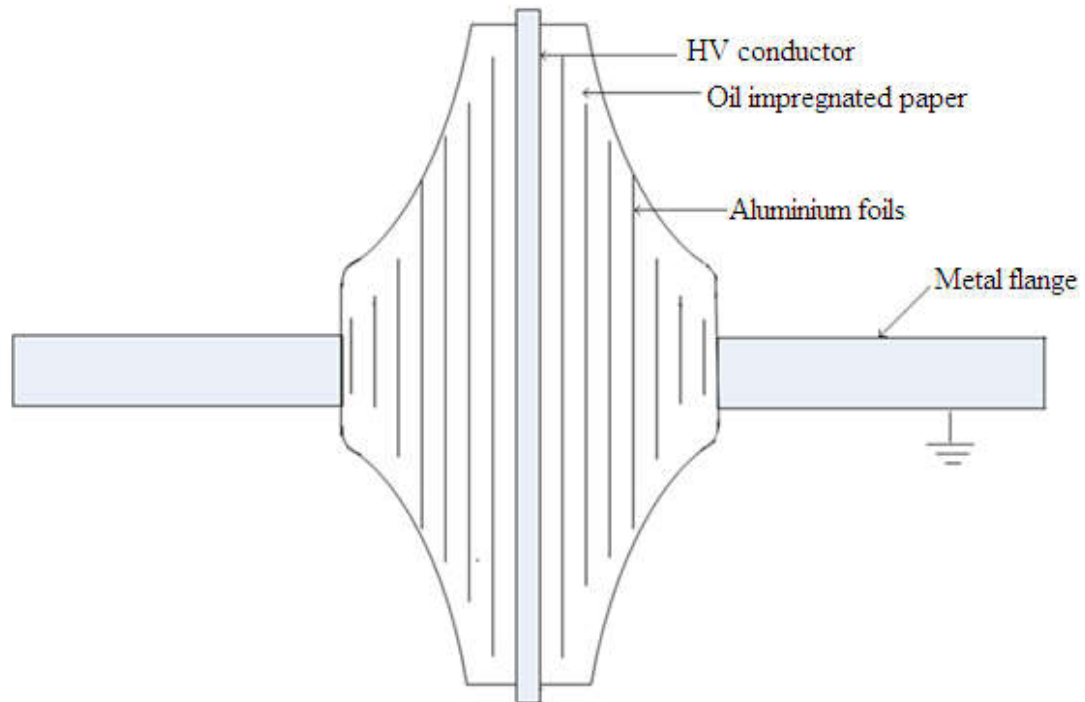
Figure 2: Capacitor type bushing (Ahmed 2011:10).

Ryan (2001), Ahmed (2011) and Septyani *et al*. (2011) state that there are three types of capacitor-type bushings, which are resin-impregnated paper insulation (RIP), resin-bonded paper insulation (RBP) and oil-impregnated paper insulation (OIP). The insulation medium for the OIP bushing is paper which is wound and impregnated with oil.

2.4   BUSHING INSULATION FAILURES

The classification of bushing insulation depends on the type of insulating material found inside the bushing. That is why the type of insulating material found in bushings can be used to determine the numerous problems associated with bushings. For example, the porcelain can prevent conductive coating - if it is used as an insulating material in bushings. It can also prevent PD from occurring since the clearance between metal flange and porcelain is provided; however, the shaft together with the conducting tube is directly embedded in a cast resin type case (Ahmed 2011).

According to Jimoh, Mahlasela and Nicolae (2005), high voltage bushings are part of the most vulnerable power system equipment because they are subjected to high dielectric and thermal stresses. A condenser-type bushing's failure results in a transformer breakdown. Table 1 shows the different problems that can occur and their methods of detection.

Table 1: Common causes of bushing problems and different methods of detection (Testing and Maintenance of High Voltage Bushings 2000).

Bushing problems		
Problem	**Likely to happen**	**Methods of detection**
Damaged porcelain	Wetness in oil and/or gas leakages. Filler leaking out.	Visual check. Power factor testing. Hot collar testing – method of measuring the Insulation Power Factor of porcelain bushings.
Deterioration of cemented joints	Wetness in oil and/or gas leakages. Filler leaking out.	Visual check. Power factor testing. Hot collar testing.
Gasket leakages	Wetness in oil and/or gas leakages. Filler leaking out.	Visual check. Power factor testing. Hot collar testing. Hot-wire testing for wetness. Insulation resistance.
Wetness in insulation	Moisture entering	Power factor testing. Hot collar testing.

Bushing problems		
Problem	Likely to happen	Methods of detection
Solder seal leakages	Moisture entering. Filler leaking out.	Visual check, power factor test. Hot collar testing. Hot-wire testing for wetness. Leakage detector.
Damaged connection between ground sleeve and flange	Sparking in apparatus tank or within bushing. Polluted oil.	Power factor testing.
Cavity in compound	Interior corona.	Hot collar testing. Power factor tip up testing.
Oil migration	Filler contamination	Visual check. Power factor testing. Hot collar testing.
Displaced grading shield	Internal sparking discolours oil.	Hot collar testing.
Electrical flashover	Fractured or damaged porcelain. Total failure.	Visual check. Hot collar testing.
No oil	Oil leaking out. Moisture entering.	Visual check. Power factor testing. Hot collar testing.
Lighting	Fractured or damaged porcelain. Total failure.	Visual check. Lightning test.
Corona	Internal breakdown. Radio disturbances. Treeing along surface of paper or internal surfaces.	Power factor testing. Hot collar testing. Hot-wire testing. RRIV
Short-circuited condenser sections	Increased capacitance. Reduced voltage at capacitance tap terminal. Adds internal stress to insulation.	Power factor testing. Voltage testing at capacitance tap. Capacitance testing.
Darkened oil	Radio interference, Poor test results.	Power factor testing. Hot collar testing.

2.5 PARTIAL DISCHARGE DETECTION METHODS

Karmakar, Roy and Kumbhakar (2009) and Markalous, Boltze, Bolliger and Wilson (2009) report that, the gradual degradation of HV transformer insulations caused by partial discharges, is a result of cumulative effects of electrical, chemical and mechanical stress. The methods used for partial discharge measurement include

chemical, acoustic, electrical and radio frequency detection methods (Lazarevich 2003; Karmakar *et al.* 2009).

2.5.1 Chemical detection method

Karmakar *et al.* (2009) state that partial discharges in HV power insulation equipment can be detected by monitoring the changes in the chemical composition of the insulation. In their work, Lazarevich (2003) and Karmakar *et al.* (2009) report that the dissolved gas analysis (DGA) and high performance liquid chromatography (HPLC) are widely-used diagnostic methods for chemical detection in partial discharge evaluation. Insulating oil during breakdown releases small quantities of gases when subjected to electrical or thermal stress. The composition of these gases depends on the type of fault (Verma 2005). Schwarz and Muhr (2008) reported that the DGA is carried out by taking an oil sample in order to determine the levels of different dissolved gases such as hydrogen, oxygen, nitrogen and carbon dioxide. The presence of partial discharges indicated by the analysis conducted provides additional diagnostic information because different levels of each of the gases can be correlated to a specific type of fault inside the transformer using extensively-developed tables (Lazarevich 2003; Schwarz & Muhr 2008).

On the other hand, HPLC measures the by-products of the transformer's insulation breakdown such as degraded forms of glucose produced due to the degradation of the insulation (Lazarevich 2003; Karmakar *et al.* 2009).

Finally, in their recent work, Schwarz and Muhr (2008) mention that the investigation of the colour appearance, acidity, neutralisation value, interfacial tension, sludge content, particle count and corrosive sulphur are the important chemical diagnostic methods for determining the level of oil in the transformer.

2.5.2 Acoustic detection method

According to Ramírez–Niño and Pascacio (2009), the most suitable alternative method for on-line partial discharge detection in power transformers is the acoustic method. The authors report that the sensors can be placed on the grounded transformer's tank at any point of the wall in a safe way in order to detect the

acoustic emission of partial discharges. Partial discharge detection through an acoustic emission method is based on the detection of the mechanical signal emitted from the discharge (Kumar, Gupta, Udayakumar & Venkatasami 2008). In addition to that, the authors stated that the induced form of an electromagnetic signal that propagates throughout the insulation is as a result of the appearance of a small explosion of the discharge. The output is analysed using a conventional data acquisition system that has a suitable sensor used to detect the wave. However, the shape of the signal detected depends on the source, detection equipment and the sensor.

The partial discharge acoustic detector is made up of a set of piezoelectric ultrasonic sensors with a resonant frequency around 150 kHz. The sensor consists of an amplifier that couples the measuring impedance to be transmitted via double-shielded coaxial cables to the measuring equipment. The measuring equipment produces a signal conditioning module for each sensor. However, the functions of the microcontroller control the input signal gain, the analogue/digital conversion of each signal, the measuring of arrival times, the generation of a common analogue signal to fix the detection threshold for all channels and the communication with a personal computer (PC) or local area network (LAN) via Ethernet (Ramírez–Niño & Pascacio 2009).

Work by Karmakar *et al*. (2009) reports that the acoustic method is immune to electromagnetic interference (EMI), thus the failure spot and location of discharges can be found by using the acoustic method. Moreover, Ramírez–Niño and Pascacio (2009) mentioned that it is possible to screen discharge pulses from other noise patterns by correlating the detected acoustic signals with the phase voltage. Partial discharges can easily be detected by using the acoustic method when sources are located in the insulating oil, but it is very difficult to detect partial discharges when they are located in the solid insulation system (Ramírez–Niño & Pascacio 2009). Furthermore, the authors' report that the major problem associated with the acoustic method is that its signals are attenuated and that the signals that reach the acoustic sensors do not have a suitable magnitude to be detected, whereas the electrical method is suitable to detect the partial discharge activity in many other cases.

2.5.3 Radio frequency detection method

Electromagnetic (EM) signals are detected using high frequency (HF, 3MHz - 30MHz), very high frequency (VHF, 30MHz - 300MHz) and ultra-high frequency (UHF, 300MHz - 3GHz) methods by means of couplers. The propagation of partial discharge pulses through the conductor induces EM transients in the surrounding media. The type of material and the defect determines the frequency range of the partial discharge signals. Partial discharge in transformers has a shorter rise time and thus emits higher frequency signals (De Haas 2011).

Strachan, Rudd, McArthur and Judd (2008) and Lopez-Roldan and Tang (2012) report that, the detection of partial discharges in transformers using UHF has increased in recent studies. An EM signal is radiated when a partial discharge occurs inside a transformer that resonates in the tank, which can be detected by UHF sensors (Strachan *et al.* 2008). Experimental evidence suggests that only a few interferences can be detected using the UHF method, irrespective of the complex nature of the transformer's internal structure. Barriers in the insulation have little influence on the sensitivity of the UHF partial discharge measurement (Agoris *et al.* 2005).

Markalous *et al.* (2009) used the UHF method to determine partial discharge in a 110 kV transformer located very close to a communication tower. Despite the screening to the UHF sensor by the transformer's tank, the visibility of the narrow-band UHF spectrum (all are modulated carriers) still existed, but the selection of a frequency below 1GHz was enough to eliminate the noise.

2.5.4 Electrical detection method

Karmakar *et al.* (2009) describe the electrical detection method as the most popular method for partial discharge measurement in transformers. Also, Schwarz, Muhr and Pack (2005) state that electrical methods depend on the electrical and electromagnetic effects of the partial discharges; thus, this method is used for the detection of currents, voltages or existing electromagnetic fields (Schwarz *et al.* 2005).

The electrical detection method focuses on capturing the electrical pulse created by the current streamer in the void. Direct probing, which requires capacitive couplers to be connected to the phase terminals of the transformer and RF emission sensing, which is conducted by using antennas in the area of the transformer, are examples of electrical detection methods (Kumar *et al.* 2008).

Moreover, Karmakar *et al.* (2009) report that both narrow band and broad band electrical noises are produced during the operation of HV transformers. However, the pulses last for about one nanosecond and have measurable frequency components in the range of 10 kHz to 1 MHz. The problem associated with the electrical detection method is its susceptibility to noise (Lazarevich 2003).

A circuit for partial discharge detection, according to SANS and IEC 60270 standards, is shown in Figure 3. This circuit consists of the power supply, coupling capacitor (C_k), test object (C_a), and detection impedance (Z_{mi}). "The apparent charge q of a PD pulse is that charge which, if injected within a very short time between the terminals of the test object in a specified test circuit, would give the same reading on the measuring instrument as the partial discharge current pulse itself. The apparent charge is usually expressed in pico coulombs (pC)" (SANS & IEC 60270:2000). In a nutshell, the main advantage of this method is its accuracy and accessibility of the information about intensity, source and possible fault type. However electrical interference during measurement is the main disadvantage (Walker 2013).
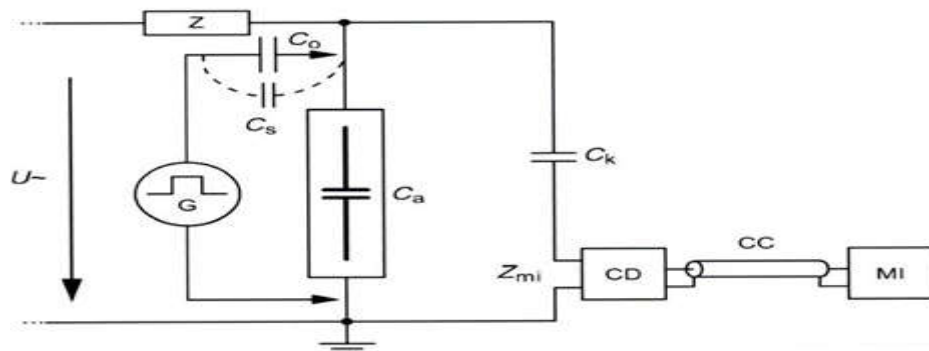
Figure 3: Circuit for measurement of the apparent charge (SANS & IEC 60270:2000)

There are many different methods which can be used to evaluate the condition of a transformer. The phase-resolved method was appropriate for the measurements using electrical method of partial discharge detection because it can easily identify the different defects and their location compared to other methods such as the acoustic method and the Dissolved Gas Analysis.

2.6 TRANSFORMER INSULATION

Hardie (2006) reports that insulation is the most crucial part of a transformer as itisolates the live parts from the surroundings. The insulation prevents the load current from flowing unintended paths. Malik, Al-Arainy and Qureshi (1998) state that the materials used for electrical insulations are numerous in the electrical power industry. The various classification of insulating materials are gases, liquid, solids and vacuum (Malik *et al*. 1998; Okabe, Hayakawa, Murase, Hama & Okubo 2006).

Verma (2005) mentions that the insulating materials are the ones that provides a relatively high resistance to the passage of an electric current. In addition to that, the author reports that the insulating materials are of different characters in terms of their origins and properties and the most commonly used insulation materials in transformers are resins, wax, glass, ceramics, paper, oil and mica. Table 2 shows the dielectric constant of various insulation materials.

Table 2: Dielectric constant of different materials (Herman 2007:103)

MATERIAL	DIELECTRIC CONSTANT, K
Air	1
Paper	2,0 – 2,6
Insulating oils	2,2 – 4,6
Mica	6,4 – 7,0
Pyrex glass	4,1 – 4,9
Cellulose acetate	7,0

2.7   TRANSFORMER INSULATION AGEING

According to Flanagan (1993), "the life span of a magnetic device depends upon its insulation system". The author states that electrode geometry, composite dielectrics, temperature gradients and compatibility among different materials affect the characteristics of an insulation system, thus making the prediction of systems characteristics from the properties of individual materials, uncertain.

Shugg (2002) states that the transformer insulation system is a combination of insulation materials found in HV transformers. The most important part of HV transformers is the electrical insulation system, with respect to the factory costs as well as the maintenance and lifetime aspects (Farahani, Gockenbach, Borsi & Kaufhold 2008). The use of the electrical insulation of a large transformer is based on how the insulation can withstand the widely different electrical, mechanical and thermal stress existing in the HV transformer during operation (Farahani *et al*. 2008; Shugg 2002).

Moreover, Shugg (2002) reports that the arrangement of its individual components, the interaction with each other and the contribution of each component to the electrical and mechanical integrity of the system determines the length of the useful life of the insulation system of the HV transformer. The main active parts of the transformer insulation are paper insulation, insulation oil, bushing and on-load tap changer systems (Kovacevic, Skundric & Lukic 2006).

In their work, Kovacevic *et al*. (2006) explain that chemical reactions occur during the ageing process in the oil/cellulose insulation system under thermal stress. The authors report that the temperature of the oil/paper dielectric is the critical ageing parameter causing enough change in the mechanical and electrical properties of the material. The presence of water content and oxygen in the system is an important parameter affecting the ageing of the solid and liquid insulations (Kovacevic *et al*. 2006).

2.8 SUMMARY

In this chapter, the literature review covering the field of PDs in high voltage bushings and transformers were presented. The type of bushings, bushing insulation failures, transformer insulations and the different causes of ageing of the transformer's insulation system were reviewed.

CHAPTER THREE: THEORY OF PARTIAL DISCHARGE

3.1 INTRODUCTION

Partial discharge is defined as "a localised electrical discharge that only partially bridges the insulation between the conductors and which may or may not occur adjacent to a conductor" (SANS & IEC 60270:2000). The theory of partial discharge is discussed in detail in this chapter. It includes the partial discharge mechanism, partial discharge modelling, corona discharge and partial discharge detection methods in general. This chapter also discusses partial discharge in power transformers, partial discharge monitoring in transformers, partial discharge location in transformers, the problem of noise and the signature of partial discharge in electrical insulating materials.

3.2 THE PARTIAL DISCHARGE MECHANISM

According to Wadhwa (2007), corona or gas discharge, surface discharges in laminated materials on the interfaces of different dielectric materials, cavity discharges and treeing channels are the main examples of partial discharges. Partial discharge is mainly caused by cavities within the solid and liquid dielectrics (Fidan & Ismailogh 2007).

The existence of either a highly non–uniform electric field or a situation where the insulation has a weak point such as a gas-filled void, usually results in the occurrence of a partial discharge, which limits the lifetime of an insulation system due to its deteriorating effect (Niasar 2012). The author also further states that high - energy electrons or ions cause the deterioration of the insulation material during partial discharge phenomenon on the surface or inside an insulation material. Thus, this bombardment may result in chemical and physical decomposition in the insulation material, which could finally result in the complete breakdown of the insulation system.

Furthermore, work by Vahidinasab, Mosallanejad and Gholami (2005) indicate that the void can be found in the following areas; between the copper conductor and the insulation wall as well as in the insulation wall itself; or between the outer insulation wall and the grounded frame and on the surface of the insulation material. In their work, Paoletti and Golubev (1999) and Vahidinasab *et al.* (2005) identify the different possible locations of voids within the transformer insulation system as shown in Figure 4 and Figure 5.
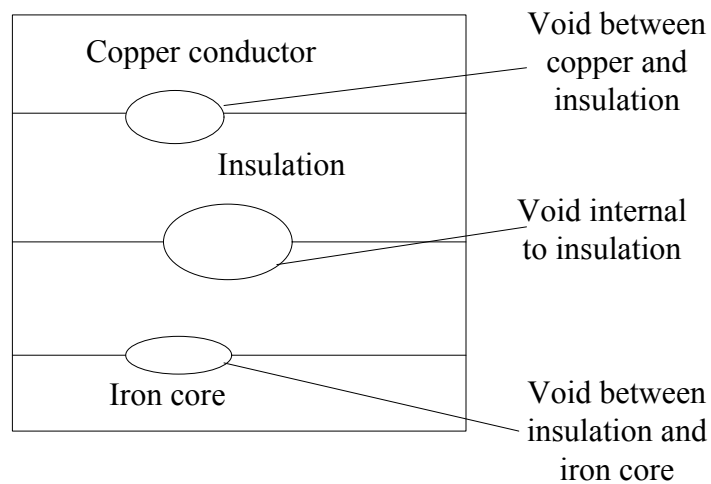
Figure 4: Voids in insulation systems (Paoletti & Golubev 1999:125; Vahidinasab *et al.* 2005:1301).
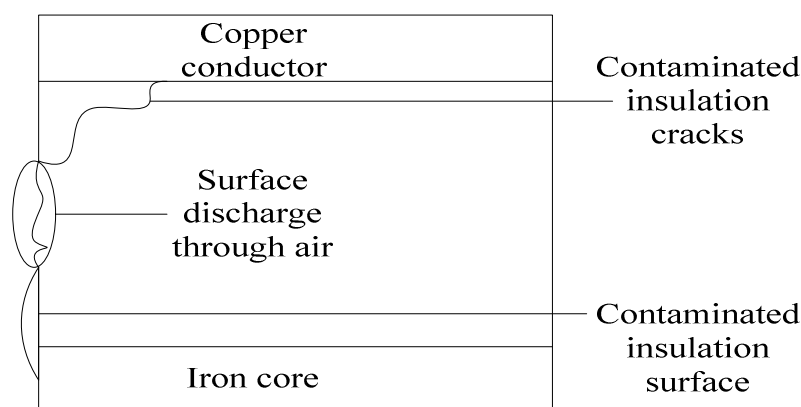
Figure 5: Surface partial discharge (Paoletti & Golubev 1999:125; Vahidinasab *et al.* 2005:1301).

3.3 TERMINOLOGIES IN PARTIAL DISCHARGE

The terms used in partial discharge are:

- Discharge detector – It is an instrument used to either detect or measure the discharges (Rao & Shukla 2011).

- The PD inception voltage – It is the applied voltage at which initial partial discharge is established when the voltage is increased gradually from a lower level where there is no partial discharge (Naidu & Kamaraju 1995; Ryan 2001).

- The PD extinction voltage – It is the minimum voltage level at which repetitive partial discharge ceases to occur when the voltage is gradually reduced from a higher level to the lowest level where no partial discharge is recorded (Naidu & Kamaraju 1995; Ryan 2001).

- Discharge magnitude – It is the quantity of charge, as measured at the terminals of a single discharge (Naidu & Kamaraju 1995; Rao & Shukla 2011).

3.4 PARTIAL DISCHARGE MODELLING

The equivalent circuit used to evaluate the fundamental quantities related to a partial discharge pulse is shown in Figure 6. This circuit consists of two electrodes, A and B, and a gas-filled cavity separated by solid or liquid dielectric materials (Gui, Gao, Tan & Gao 2003).

In their work, Khalifa (1990); Nafar, Abedi, Gharepetian, Taghipour & Yousefpour (2004); Wadhwa (2007); and Rampersad (2010) report that the equivalent circuit of a dielectric incorporating a cavity can be modelled as a capacitive voltage divider in parallel with another capacitor, as shown in Figure 6.
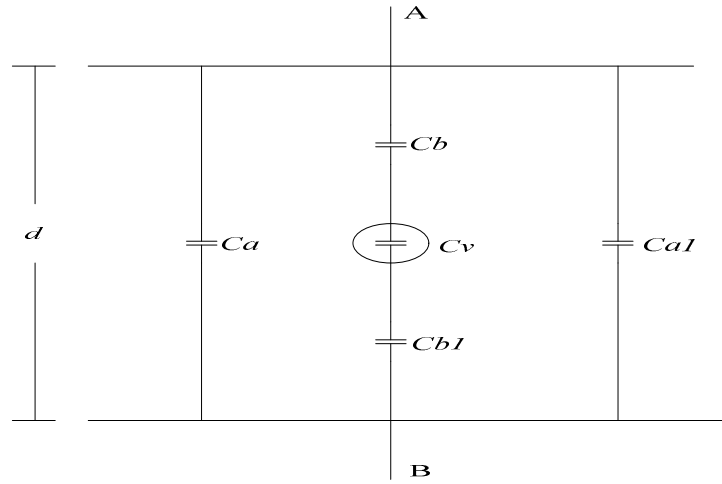
Figure 6: Equivalent circuit (Wadhwa 2007:182)

C_b and C_{b1} are capacitances in the solid insulation area in series with the void, C_v represents the void while C_a and C_{a1} are the remaining capacitances of the dielectric.

According to Liu, Phung, James, Blackburn and Ariastina (2001), the actual charge changes occurring due to a partial discharge event at source are usually not directly measurable, but it is rather the apparent charge that is measured. Therefore, it is the change in charge that, if injected between the terminals of the device under test, would change the voltage across the terminals by a magnitude equivalent to the partial discharge level. Figure 7 illustrates the simplification of Figure 6.
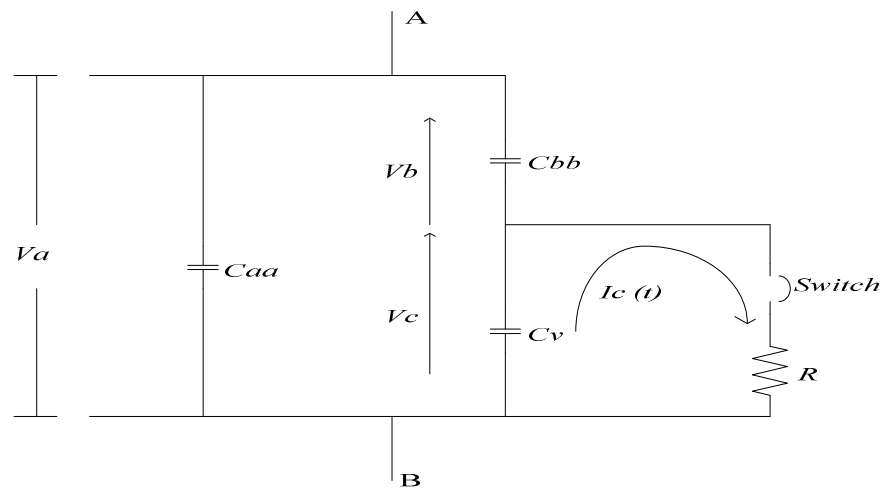
Figure 7: Simplification of Figure 6 (Kuffel, Zaengl & Kuffel 2000: 424)

$$C_{aa} = C_a + C_{a1} \text{ and } C_{bb} = C_b C_{b1} / (C_b + C_{b1}).$$

The capacitance of a parallel electrode set up separated by a dielectric is given by;

$$C = \frac{\varepsilon_o \, \varepsilon_r \, A}{d} \qquad (1)$$

Where,

ε_o = permittivity of free space = 8.854×10^{-12} Fm^{-1}

ε_r = relative permittivity,

A is the area between electrodes,

d is the separation of electrodes.

Assuming the gas within the void (width Dx) in Figure 7 has a relative permittivity of nearly 1, then:

$$V_v = \frac{C_{bb}}{C_v + C_b} \qquad (2)$$

But,

$$C_{bb} = \frac{C_b C_{b1}}{C_b + C_{b1}}$$

$$V_v = \frac{C_b}{C_v + C_b} \, V_a$$

But,

$$C_b = \frac{\varepsilon_o \varepsilon_r A}{d - D_x} \qquad (3)$$

$$C_v = \frac{\varepsilon_o \varepsilon_{air} A}{d - D_x} \qquad (4)$$

Therefore,

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$$V_v = \frac{\frac{\varepsilon_o \varepsilon_r A}{d - D_x}}{\frac{\varepsilon_o A}{D_x} + \frac{\varepsilon_o \varepsilon_r A}{d - D_x}} \, V_a$$

Assume $\varepsilon_{air} = 1$

$$V_v = \frac{\frac{\varepsilon_r}{d - D_x}}{\left(\frac{1}{D_x} + \frac{\varepsilon_r}{d - D_x}\right)} \, V_a$$

$$V_v = \frac{\varepsilon_r}{\frac{d - D_x}{D_x} + \varepsilon_r} \, V_a$$

$$V_v = \frac{V_a}{\left(1 + \frac{d - D_x}{\varepsilon_r D_x}\right)}$$

$$V_v = \frac{V_a}{1 + \frac{1}{\varepsilon_r}\left(\frac{d}{D_x} - 1\right)} \tag{5}$$

Thus, the electrical field strength across the void (E_v) equals:

$$E_v = E_a \frac{d}{D_x\{1 + \frac{1}{\varepsilon_r}\left(\frac{d}{D_x} - 1\right)\}} \tag{6}$$

It can be noted that, electrical stress within the void is larger than that in the immediate insulation, since $Dx \ll d$ and ε_r is greater than 1 in most cases. This makes the gas within the cavity responsible for the breakdown when the usual operational conditions are not adequate (Smith 2005).

According to Smith (2005), it is noted that, the voltage across the dielectric at which discharge action will start within the void, V_{ai} is given by:

$$V_{ai} = E_{vb} D_x \left\{1 + \frac{1}{\varepsilon_r}\left(\frac{d}{D_x} - 1\right)\right\} \tag{7}$$

Where, E_{vb} is the breakdown strength of the gas in the void.

In practice, voids in solid insulators are very often approximately spherical. The field in the void in this case is:

$$E_v = \frac{3 E_a \varepsilon_r}{\varepsilon_{rc} + 2\varepsilon_r} \qquad (8)$$

Where, ε_{rv} is the relative permittivity of gas in void. When $\varepsilon_r \gg \varepsilon_{rv}$, this approximates to:

$$E_v = \frac{3}{2} E_a \qquad (9)$$

The electric field inside the cavity increases when the voltage between electrodes A and B increases, as shown in Figure 7. Partial discharge occurs when the voltage across the cavity reaches the breakdown value of the gas-filled void. When the switch S, is closed, a discharge current i_c, flows for a short time. The resistor R ensures that the magnitude of the current is limited. When a voltage V_a is applied to A and B, causes V_v, across the void to reach the breakdown strength of the air, there is another breakdown. The voltage across the capacitor C_v increases as it charges. When the discharge current is extinguished, the capacitor C_v starts to charge up once again. The same process repeats for the next occurring partial discharge. Charging and discharging of the capacitor C_v result in PD current pulses (Kuffel *et al*. 2000). Figure 8 shows how PD pulses are generated in relation to the voltage applied.
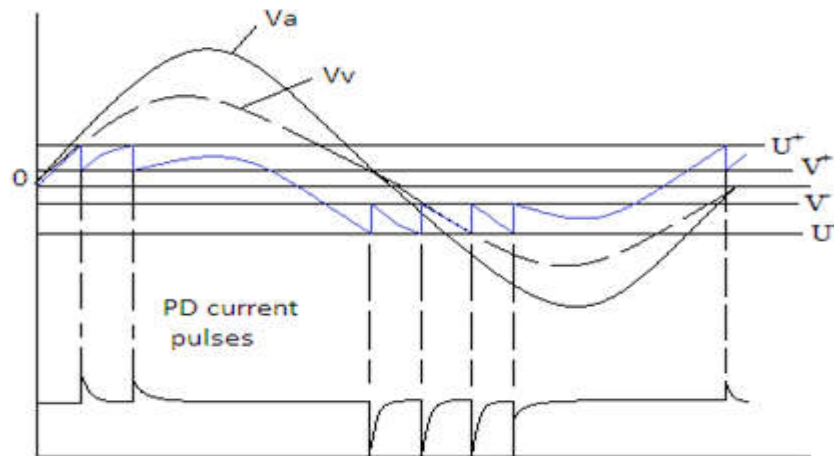
Figure 8: Voltage and current in discharging void (Kuffel *et al*. 2000:383)

When the voltage V_a is applied, V_v reaches the breakdown voltage of the medium inside the cavity (U^+). The voltage V_v subsides to V^+ and the discharge is quenched. The voltage rises again and another discharge takes place. This process repeats throughout the increasing session of the applied voltage. The applied voltage decreases with an increase in the voltage across the void in the reverse polarity. When it reaches U^-, a partial discharge pulse occurs with negative polarity and the voltage across the void drops to V^-. The phenomenon repeats in the next half cycle (Naidu & Kamaraju 1995; Kuffel *et al.* 2000; Ryan 2001; Smith 2005; Fidan & Ismailoglu 2007).

3.5   PARTIAL DISCHARGE IN POWER TRANSFORMERS

The presence of partial discharge in a large transformer is an indication of insulation deterioration and ageing, which result in a local breakdown of insulation in a high voltage transformer occurring in gas bubbles in the oil or voids in solid insulation materials (Gross & Söller 2004; Schwarz & Muhr 2008).

Gross and Söller (2004) also state that the oil-paper insulation tolerates partial discharge activity in a high voltage transformer up to a certain level, but an insulation type like polyethylene does not. Partial discharge testing is excellently suited to assess the condition of the large transformer's insulation (Gross & Söller 2004; Schwarz & Muhr 2008).

3.6   PARTIAL DISCHARGE MONITORING IN TRANSFORMERS

Partial discharge in transformer can be monitored through the bushing tap. The bushing adapter is connected to the bushing tap, which also provides protection in over-voltage conditions.

The bushing tap, which is a component of capacitance graded bushings, provides a control layer insulated from the flange from the outside, which divides the total capacitance of the bushing into two: C_1, (HV conductor test layer), and C_2 (test layer flange). It is used to measure the capacitance C_1 and its loss factor tan δ and can also be used to do a permanent voltage measurement or PD monitoring (MICAFIL 1999).

Then, the coupling units of the transformer's bushing are connected to the bushing tap of the transformer (Gross & Söller 2006). Figure 9 shows the schematic diagram of a bushing tap connection.
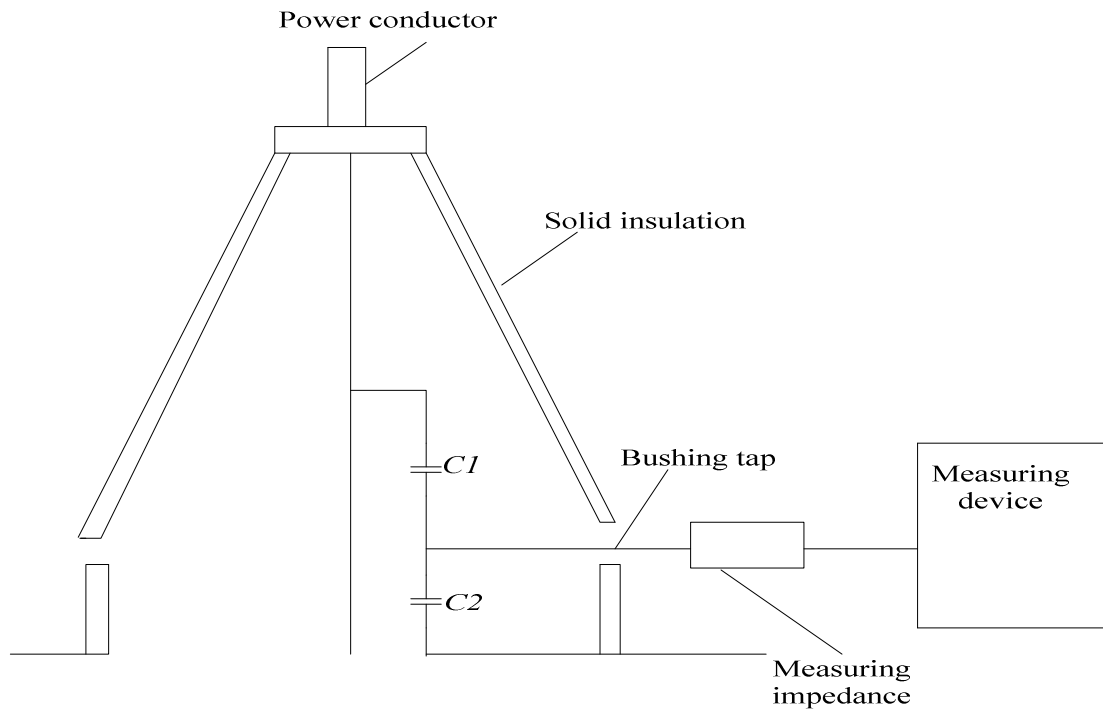
Figure 9: Schematic diagram of a bushing tap

The partial discharge monitoring system has been incorporated to enable the visual monitoring of the partial discharge pulses produced in the transformer.
The ICMmonitor is an example of autonomous device, which is used to monitor the activities of partial discharge in a high voltage transformer.

3.7   PARTIAL DISCHARGE LOCATION IN TRANSFORMERS

Partial discharge location in a power transformer is one of the major features of the electrical discharge detection method (Gui *et al*. 2003). "With the indications of the presence of internal discharge within a large power transformer, further measures must be taken to narrow down the possible location of the discharge activity" (Gross & Söller 2005). The determination of a partial discharge type and location depends on the analysis of the shape of the partial discharge signal in the time domain. The

frequency spectrum analysis of the partial discharge signal can also be used to determine the type of partial discharges, and where they are localised (Kumar, Gupta, Venkatasami & Udayakumar 2009).

Moreover, Menon, Kolambekar, Buch and Ramamoorty (2001) report that the location of partial discharges in a transformer depends on their geometrics, as well as their PD magnitude.   The relationship between the difference in properties and the partial discharge positions, according to the partial discharge source positions, provides some information for partial discharge location (Gui *et al*. 2003).

3.8   BASIC CONCEPTS

Partial discharges are by definition only confined to a part of the electrical insulation system. The different types of discharges are defined as follows:

- Surface discharges – These are partial discharges occurring on the surface of the solid insulation not covered by the conductor or discharges from the conductor into a gas or a liquid medium (Rao & Shukla 2011).

- Internal discharges – These are discharges in the cavities or voids, which lie inside the volume of the dielectric or at the edges of conducting inclusions in solid or liquid insulating media (Naidu & Kamaraju 1995; Rao & Shukla 2011).

- Corona discharges – These are external partial discharges occurring in gases or liquid insulations from sharp edges of electrodes which are not inside the solid insulations. They are caused by a locally enhanced field. Corona discharges are accompanied by a number of observable effects such as visible lights, audible noise, electric current, energy loss, radio interference, mechanical vibrations and chemical reactions. Panicker (2003) states that corona discharge is used in air purification to clean air by way of ionising the air. The author also states that, the ozone is a by-product of a corona discharge. It is used to

kill microbes and neutralise airborne contaminants. Therefore, corona is often harmless, but its by-products such as ozone and nitrogen oxides may chemically deteriorate materials in close proximity (Khalifa 1990).

3.9   SURFACE DISCHARGES

According to Ahmed (2011), surface discharge is a kind of PD that occurs along the surface of solid insulation in contact with gas or liquid insulation. The concentration of partial discharges in one area results in the local carbonisation of that specific region, particularly in the case of organic plastic material. The local carbonisation reduces the creepage distance. The degradation of the insulation accelerates due to electrical stress on the surface. Infra-red spectroscopy is used to detect a partial discharge in polymer materials. During carbonisation, carbon radicals are formed, which results in peroxide radicals after reaction with oxygen. The formation of radicals as a result of polymer chain breakage causes irreversible oxidation of insulating materials. The formation of sharp peaks of crystals increases the partial discharges' concentration if the materials are stressed tangentially for a longer period of time. This finally leads to a complete breakdown.

Polymer materials are sensitive to partial discharge because charge carriers enter the insulating materials. They are captured in homogeneities inside the molecules and crystalline structure. The examples of these in homogeneities are branches, terminal points of chain molecules crystalline boundaries and boundary layers. The local electric stress is developed without any change in load stress. The temperature is also a very important parameter for the evaluation of partial discharge sensitivity (König & Rao 1993).

The electric field is changed after the occurrence of the discharge affecting the healthy portion of the insulation as the discharge is extended into that region. The size of a discharge is unequal in the opposite polarities when an alternating voltage is applied. There are small discharges for a negative electrode and large discharges for a positive electrode because of the movement of positive and negative charges (König & Rao 1993).

Leakage current via the conducting film on the insulation's surface, for example aluminium foil on paper, is also a source of surface discharge. There are certain stresses that occur in an organic solution. They are:

- The electrochemical stress: The electromechanical stress is the main problem of organic insulation and

- The mechanical stress: The mechanical stress increases the destruction process of organic insulations when polymer materials are tested regarding surface discharge resistant properties; the mechanical stress and the surface discharge occurs simultaneously.

Organic materials have a short life when surface discharge is present. Surface discharge is observable from light emission or it can be detected by a voltage pulse. In the voltage pulse technique, it gives an asymmetric pulse pattern. If the applied voltage is increased, the pulse height increases (König & Rao 1993; Gallagher & Pearmain 1983). Figure 10 shows surface discharges occurring on the surface of the insulation.
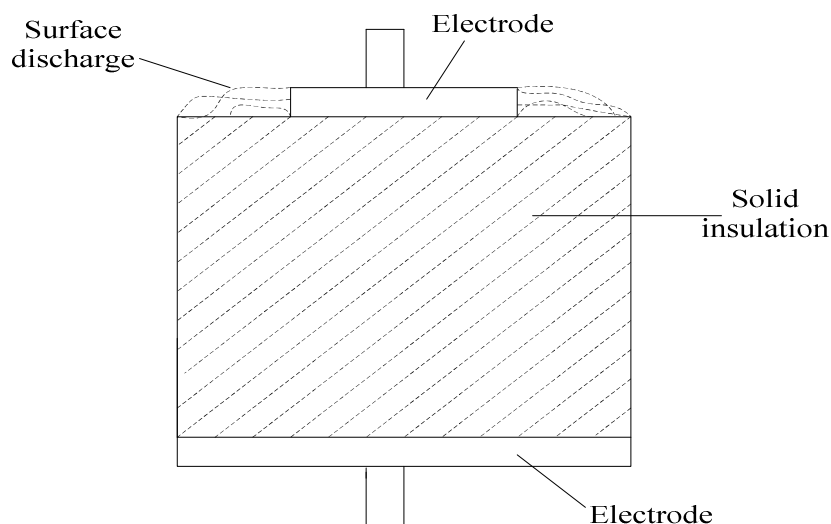
Figure 10: Surface discharges occurring on surface of insulation (Ahmed 2011: 22)

3.10 INTERNAL DISCHARGES

The electric field in air-filled cavities is higher than the electric field in the materials because of the difference in their dielectric constants as well as the shape of the cavity. In solid insulating materials cavities are of irregular shape.

The cavities in solid insulations can be broken down as a result of the presence of certain particles such as metallic particles, the presence of a charge on the cavity and semi-conducting deposits on the surface of the cavity. Figure 11 illustrates an air – filled cavity in solid insulation.
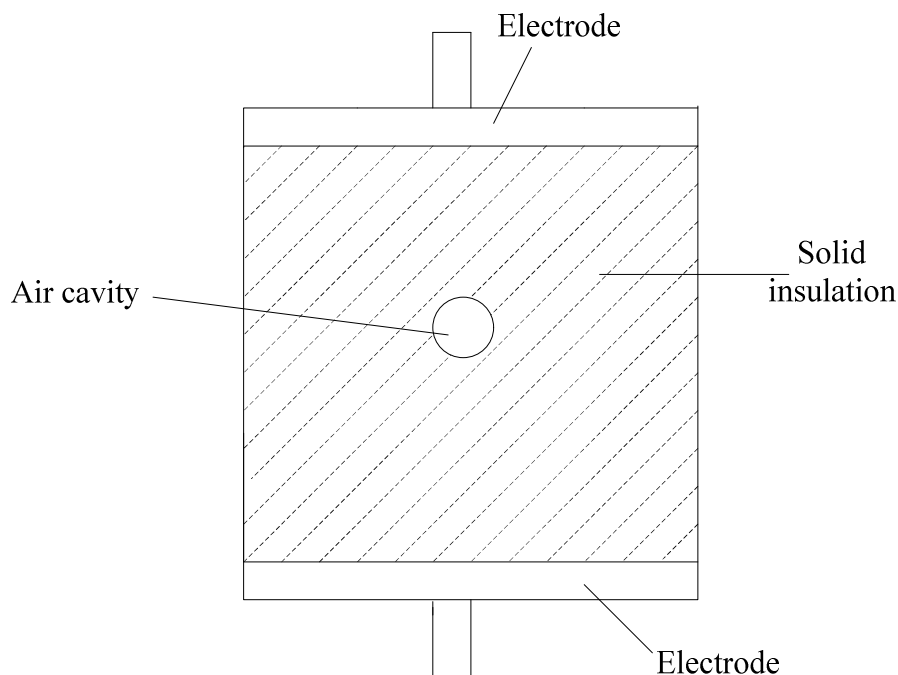
Figure 11: An air-filled cavity in solid insulation (Ahmed 2011: 23)

A void filled with air can cause breakdown at atmospheric pressure (101.03 kPa). It occurs at a normal operating voltage and because of this very breakdown, the charges on the cavity are transferred to the opposite side surface, but a few charges are left on the surface of the cavity. These remaining charges change the electric field of the cavity and the next discharge takes place at different locations of the cavity. When an alternating voltage is applied, the discharges of opposite polarities are produced

alternatively. There are charge clusters of opposite polarities at different sites of the cavity that result in discharge on the cavity's surface inside the insulating materials (König & Rao 1993; Gallagher & Pearmain 1983).

A conducting channel is formed between the electrodes that bridge the cavity. It results in insufficient voltage for the breakdown of gas and at the end, the discharge extinguishes. The extinction voltage is less than the inception voltage because after the initial discharge, a lower voltage is required to maintain the discharge; it can be up to 25 % lower in many cases. If cavities are small (< 0.15 mm) and filled with air at atmospheric pressure, discharges cannot be detected by pulse discharge detectors (König & Rao 1993; Gallagher & Pearmain 1983).

3.11 CORONA DISCHARGE

According to Miller (2012), corona discharge is an electrical condition that happens at or near atmospheric pressure in gases. The author mentions that it requires a strong relative electric field. The light emission and the hissing sound show the corona manifestations externally. Miller (2012) adds that the shape of the electrodes, the polarity, the size of the gap and the gas mixture determine the characteristics of corona discharge. Finally, corona discharge results in power loss, damage to conductors and degradation of the insulators on transmission lines.

Panicker (2003) reports that corona discharge occurs in the forms of glows and haloes, spots, brushes and streamers. The author states that the corona threshold voltage is the point at which corona is found to originate. Current increases proportionally with voltage within the limited region above the corona threshold voltage. Hence, the increase in current results in arcing or sparking or in the - complete breakdown at a level known as the breakdown potential.
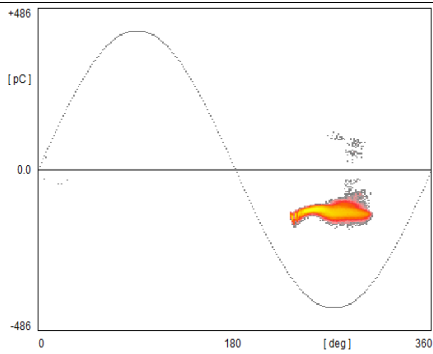
Miller (2012) reported that the potential current characteristic depends on the shape of the electrodes. The author states that the transmission from the dark current area to the field sustained discharge will be quite smooth, if the radius of curvature of the positive electrode is small compared to the gap between the electrodes.
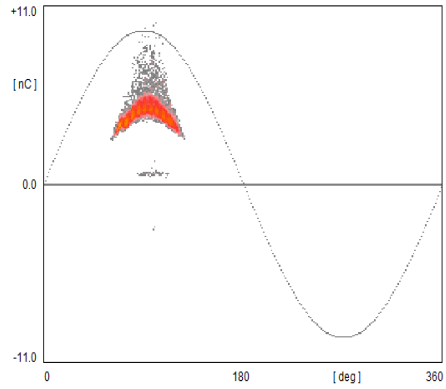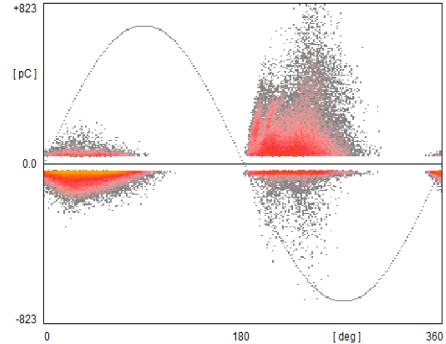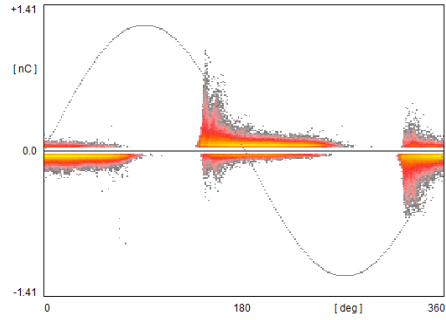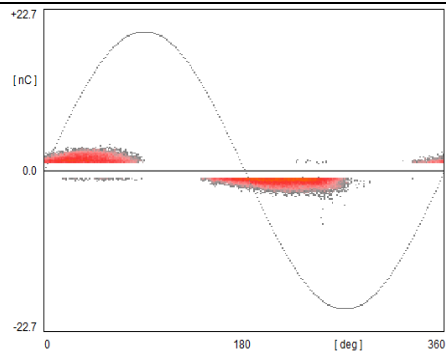
3.12   **PATTERNS OF PARTIAL DISCHARGE CAUSED BY VARIOUS DEFECTS**
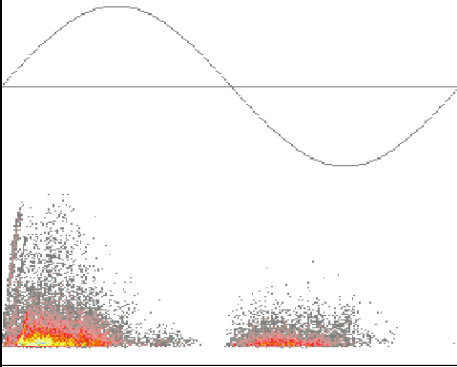
Partial discharges in solid and liquid insulations must be considered as dangerous and the degree of danger depends on the type of material used for the insulation. It is a difficult task to point out the area of occurrence of partial discharges. However, from the partial discharge pattern appearances, it can be concluded that the place of occurrence in the insulation, as well as the pattern appearance, is dependent on the location and type of defects.

In partial discharge patterns, alternating voltage is superimposed with partial discharge pulses. The time-dependent patterns can be shown on an oscilloscope (König & Rao 1993). Table 3 shows the partial discharge patterns of various defects.

Table 3: Patterns of partial discharge caused by various defects (Niasar 2012:33).

Defect type	Characteristics of partial discharge patterns	Characteristics
Negative corona in air		• Phase of occurrence: around 270° • Magnitude: small • The magnitude of the discharge depends on the radius of the sharp point and it is fairly constant with the voltage change

Defect type	Characteristics of partial discharge patterns	Characteristics
Positive corona in air		• Phase of occurrence: around 90° • Magnitude: large • The magnitude of the discharge depends on the radius of the sharp point and changes with the voltage • The number of discharges changes with the applied voltage
Surface discharge in air		• Phase of occurrence: 0 - 90° and 180 - 270° • Magnitude: small-medium • PD patterns strongly depend on the geometry of the electrodes
Surface discharge in oil		• Phase of occurrence: 330 - 90° and 150 - 270° • Magnitude: small-medium • Symmetric on both half cycles
Cavity between the layers of the paper		• Phase of occurrence: 330 - 90° and 150 - 270° • The magnitude depends on depth of the cavity • Magnitude: small-large • The repetition rate depends on the area of cavity • Symmetric on both half cycles

Defect type	Characteristics of partial discharge patterns	Characteristics
Delaminat-ion at the conductor		• Phase of occurrence: 0-90° and 180-270° • Predominantly in the positive half cycles • Non-symmetrical

3.13 SUMMARY

This chapter presented the detailed theory of partial discharge. The next chapter presents a detailed description of the experimental set up and partial discharge measurement of a HV transformer.

CHAPTER FOUR: PARTIAL DISCHARGE MEASUREMENT OF A HV TRANSFORMER

4.1   INTRODUCTION

In this chapter, the condition of a 400 V/300 000 V volts single-phase transformer (300 kV) was assessed by performing a series of phase resolved partial discharge (PRPD) measurements. The measurements were performed according to South African National Standards (SANS) (60270) and the International Electrotechnical Commission Publication (SANS & IEC 60270:2000).

4.2   PARTIAL DISCHARGE MEASUREMENT SYSTEM

The methodology followed in this study involved phase resolved partial discharge (PRPD) measurements and evaluation. PRPD evaluation is a method that displays the partial discharge activity in a three-dimensional (3D) way to identify the phase relationship, the magnitude of the partial discharge activity, and finally the discharge rate and, it is well-suited for any system on-line (Kumar *et al*. 2008).

The measurements were done using the ICMmonitor which fully complies with the requirements of IEC 60270 standards to measure partial discharges. PRPD patterns help identify the behaviour of partial discharge, its defect geometry, and the intensity of the defect (Strachan *et al*. 2008). The preferred measurement of the intensity of a partial discharge is the apparent charge (*q*) as defined in IEC 60270 publication.

The actual charge transferred at the location of a partial discharge is very difficult to measure directly (Heathcote 1998). The circuit arrangement shown in Figure 12 is mainly a conventional partial discharge test circuit consisting of a HV power supply, a 300 kV transformer (*Ct*), a coupling capacitor *Cc* and the measuring impedance *Zm*, which is detected by the measuring device.
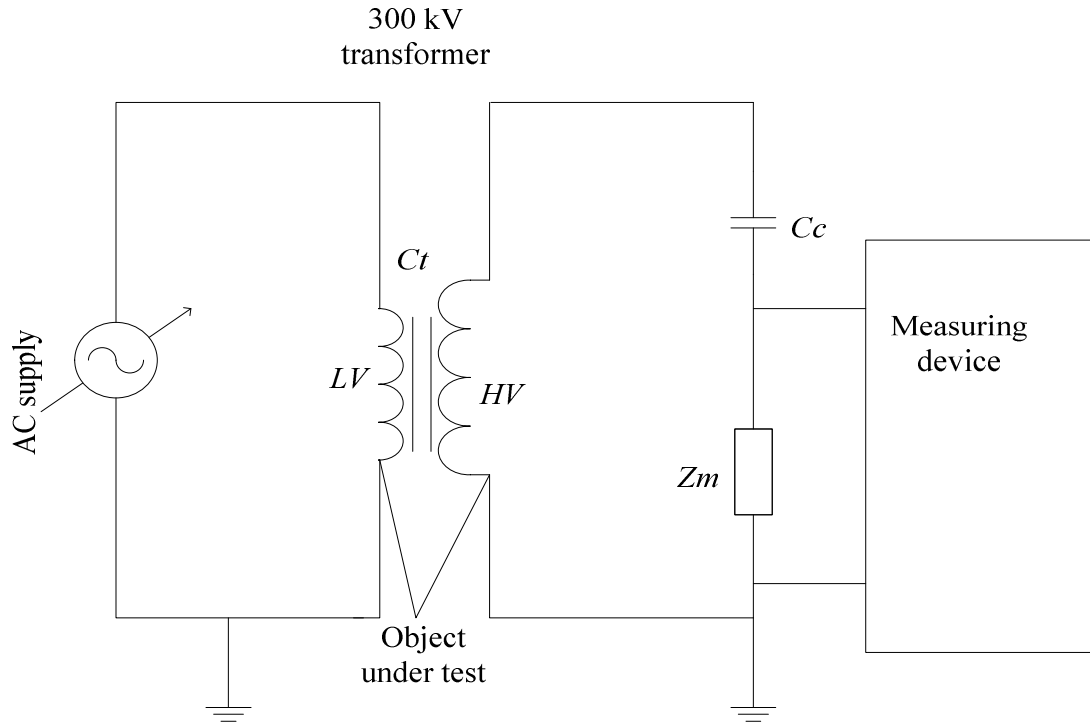
Figure 12: PD measuring circuit

When a partial discharge occurs in the test object Ct, the charge is drawn from the coupling capacitor Cc and generates a voltage impulse across the detection impedance Zm. The apparent charge transferred from Cc to the test object Ct during the discharge is measured as the voltage impulse across the detection impedance. The voltage impulse is connected by means of a coaxial cable to a pre-amplifier. The detection impedance is connected in series to the coupling capacitor, Cc.

4.3 DESCRIPTION OF THE MEASUREMENT SYSTEM

4.3.1 Power supply

Two separate voltage sources were used in these experiments. The low voltage source is produced from a 230 V, 50 Hz of which a 3,3 kVA, single-phase insulating transformer was connected to supply power to the measuring equipment. The high voltage source is produced from a regulator rated 400 V, 200 kVA, 50 Hz, supplying the 400 V/300 kV unit, controllable in voltage up to 300 kV.

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4.3.2 Tested HV transformer

The details of the tested HV transformer are provided in Table 4, and the photograph in Figure 13 shows the 400 V/300 000 V single-phase transformer.

Table 4: Name plate details of the tested HV transformer

Terms	HV Transformer
Age	46 years old
kVA	200
Volts (HV)	300 000
Volts (LV)	400
Amps (HV)	0.667
Amps (LV)	500
Frequency	50 Hz
Manufacturer	Foster Transformers Ltd.

Figure 13: A photograph of 400 V/300 000 V single-phase transformer

4.3.3 ICM monitor – digital partial discharge detector

The ICM monitor is part of the Power Diagnostix Systems GmbH ICM series of digital partial discharge detectors. The ICM monitor is a compact stand-alone instrument used to assess the condition of medium and high voltage insulation. The ICM monitor is used over a range of applied voltage frequency, including power system frequency (50/60 Hz) and very low frequency (0.1 Hz). The ICM monitor provides high-resolution, digital, partial-discharge patterns for the characterisation of defects in *inter alia* transformers and bushings.

A wide range of external preamplifiers provides control of the frequency range in which partial discharge activity is detected from 40 Hz up to 2 GHz. The ICM monitor features various noise handling techniques. The noise-gating module can be connected to an antenna or a current transformer to sense and reduce the noise to a very low level without losing significant partial discharge data. Another method available is simple windowing in which phase-stable noise is blocked out for portions of each applied high voltage wave. Similarly, a low-level discriminator (LLD) can be set to a certain level in order to reduce noise.

4.3.4 PC Software

The operating parameters of the ICM monitor are fully computer controlled making it simple to use with standard Power Diagnostix Software. The actual recording of partial discharge patterns is independent of the personal computer (PC), so the performance of the ICM monitor is unaffected by the speed limitation of the PC. The ICM monitor's PC software includes convenient options for in-depth analysis and printing of stored partial discharge patterns.

4.3.5 Calibration

Partial discharge measurements refer to the apparent charge and are relative measurements. Therefore, the system requires a calibration. To calibrate a system, the calibrator is connected to the test object and a known partial discharge pulse is injected to the system according to SANS and IEC 60270 standards. The calibrator used in this research is CAL-1A from the Power Diagnostix Systems GmbH system.

It can inject a known charge between 1 pC to 100 pC. The calibrator must be connected across the test object when the voltage is off and by using ICM software the measurement system can be calibrated. In this study a 10 pC discharge magnitude was used in the test set up.

According to Ryan (2001), the calibration pulses originate from a calibrator which produces a voltage step of amplitude V_a in series with a capacitor C_a so that the repetitive charges have the magnitude:

$$q_a = V_a C_a \qquad\qquad (10)$$

4.4 THE PROBLEM OF NOISE

Naderi, Vakilian, Blackburn, Phung and Naderi (2005) reported that any unwanted signal that is not related to the input signal is referred to as noise. Noise control during partial discharge measurement is vital because it will affect the results even with the best partial discharge device. The background noise can affect successful partial discharge tests in unshielded test laboratories and on site where the systems are exposed to a high level of noise (Russwurm 2000).

Care must be taken to reduce the background noise from radio broadcast stations, computers, cell phones, fluorescent lights, the power supply source and the terminal bushing (Heathcote 1998). Depending on the environment and the measurement circuit, different levels of interference may be visible.

4.5 CHARACTERISATION OF INSULATION DEFECTS

Experimental activity in this section forms the basis of this research work. In fact, experimental data, made available by PD measurements, provide essential information to identify the type of defects and locations of PD in the insulation of a voltage transformer.

Partial discharges occurring in solid insulations can be characterised by means of the shape of the defect, namely spherical, ellipse, cracks in the insulation and delamination on the interfaces of the electrodes. The defects were created by the researcher on the samples at pre-determined locations. The specific defect patterns obtained from the samples were then used to identify the type of defects and locations in the insulation of the voltage transformer as part of the verification method used to assess the condition of the 300 kV transformer.

The location of the defects in relation to the distance from the high voltage electrode or earth electrode also shows up in the pattern displayed. The last variable that determines the final pattern is the number of discharges occurring over a specific time.
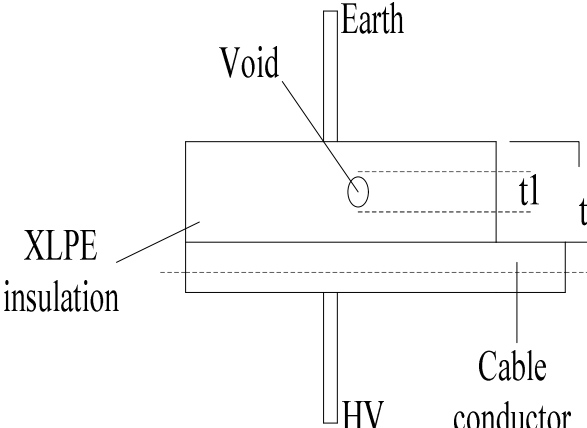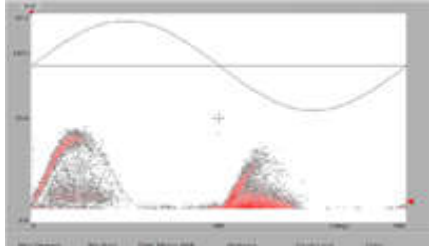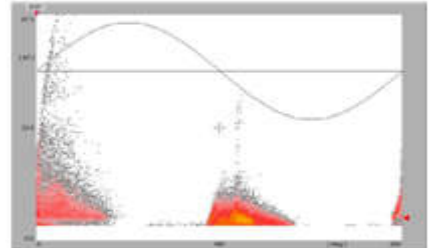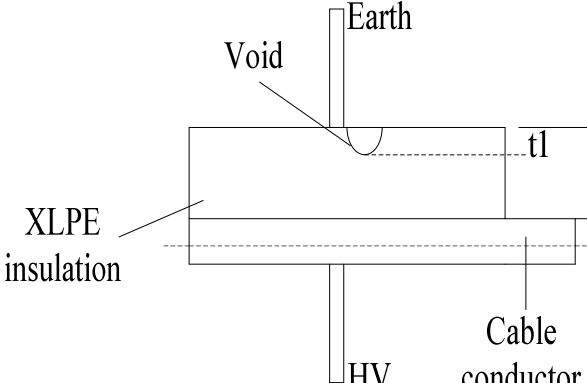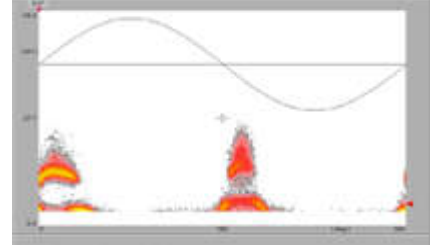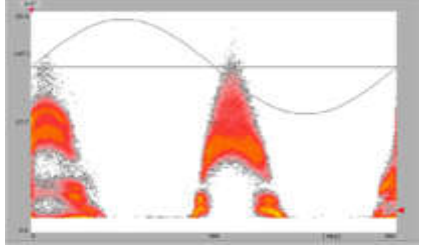
4.5.1   PDs on the insulation material with spherical void
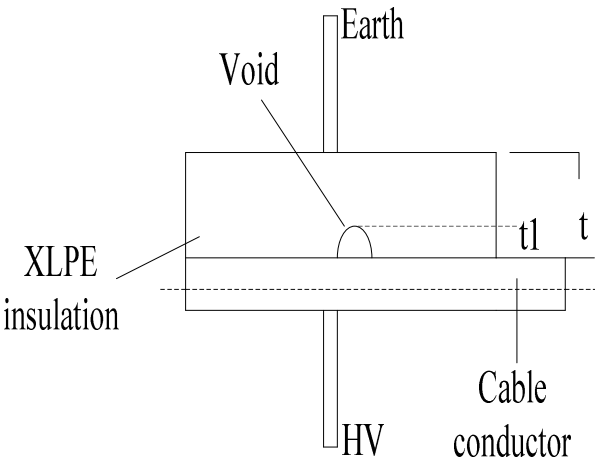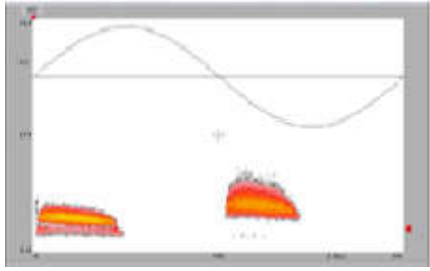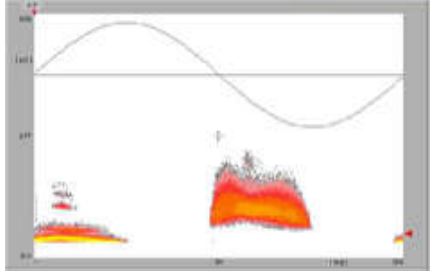
Different specimens have been set up in order to make the void to be either located close to the earthed electrode, high voltage electrode or within the insulation. The samples were made with an 11 kV cable with a hole drilled in the insulation. The thickness of the XLPE insulation was 4,6 mm. The voids were covered with a layer of heat shrink insulation (material used in cable joints and terminations) with the thickness 3,2 mm and a semi-conductive tape. The test samples were energised and partial discharge measurements were done at two different applied voltages 2,5 kV and 3 kV in order to observe the voltage effect on partial discharges. Schematics of the tested defects and their corresponding PD patterns are shown in Table 5.

The void is filled with air and the dielectric constant of the air in the voids is lower than that of the XLPE and the heat shrink insulation. Because of a lower dielectric constant in the void, there will be higher field inside the void. When the high electric field strength in the void exceeds its breakdown value a partial discharge occurs. The electric field inside the void then becomes zero after the discharge. The newly formed electrons gain speed in an electric field, ionising more molecules by impact, so that an avalanche of electrons is formed. The electrons in the avalanche and the

ions left behind move toward the electrodes, thus forming a passage of current through the gas, until the PD occurs (Lazarevich 2003; Boggs 1990).

Table 5: Typical defects and their corresponding phase-resolved patterns.

Defect type	Phase-resolved patterns
(1) void in the middle of the insulation XLPE, $\varepsilon_r = 2,3$	(a)28,4 pC at 2,5 kV (b)46,6 pC at 3 kV
(2) the void is closer to the earth Heat shrink, $\varepsilon_r = 2,5$	(a)22 pC at 2,5 kV (b)40,4 pC at 3 kV

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Defect type	Phase-resolved patterns
(3) the void is closer to high voltage 	 (a)165,2 pC at 2,5 kV (b)176,1 pC at 3 kV

The partial discharge pattern obtained, according to Gross and Herbig (2000), is determined directly by the properties of the discharging site, the availability of the initial electron to start the avalanche, the geometry of the defect and the properties of the surfaces contributing to the discharge process. On the other hand, the properties of the gas atmosphere involved indicate the partial discharge pattern. The partial discharges shown above were recorded at different applied voltages in order to observe the effects of voltage on partial discharges for samples 1, 2 and 3 respectively in table 5.

The corresponding phase-resolved patterns for the partial discharge activities of the test samples are shown in table 5. An increasing voltage of 0 - 3 kV is applied to measure the maximum partial discharge within the solid insulation. Generally, it is seen that partial discharge pulse appears around 30° - 90° phase angle in a positive

half cycle, and 150⁰ - 270⁰ phase angle in a negative half cycle of the 2,5 kV and 3 kV applied voltage. To observe PD activity within an enclosed cavity between the solid insulation and the copper, the critical materials operate as anode and cathode in the positive and negative half cycles. The cathode material provides free electrons to initiate partial discharges, which then create plasma on the surface of the insulation. Plasma accelerates partial discharge activity as it is a very good source of free electrons. As a result, there is a likelihood of partial discharge activity taking place when the insulation material is acting as a cathode (Paoletti & Golubev 2001).

For the void in middle of insulation in both positive and negative half cycles, the XLPE insulation itself remains the cathode. Therefore, there is a balance of activities within the cavity, making the partial discharge patterns obtained symmetrical between positive and negative half cycles as shown in table 5 of sample 1. When the void is located in the middle of the insulation, the electric field magnitude in the void is higher than the surrounding cable insulation, due to lower permittivity in the void as predicted by (Niasar 2012).

In the positive half cycle, the insulation acts as a cathode and the copper acts as an anode. More electrons are supplied by the insulation; consequently, there are a greater number of partial discharges in the positive half cycle than in the negative half cycles as shown in table 5 of sample 2. The corresponding patterns indicate that the cavity is located closer to the earthed electrode.

In the negative half cycle, the insulation material acts as a cathode across the cavity. The initial electrons that start partial discharges are released by the insulation; consequently there are larger numbers of partial discharges occurring during the negative half cycle as shown in table 5 of sample 3. This confirms that the cavity is closer to the high voltage electrode.

4.6   PD INCEPTION VOLTAGE

Theoretically, the inception, according to Ramachandra and Nema (1996) is calculated by:

$$V_{inc} = \frac{V_g}{\varepsilon_r} [t + t_1 (\varepsilon_r - 1)]$$ 11

Where,

V_g is the breakdown strength of the void and relative permittivity, ε_r for XLPE is 2.3.

Therefore, void inception voltage is given by:

$$V_v = \frac{V_{app}}{[1 + \frac{t - t_1}{\varepsilon_r t_1}]}$$ 12

Where,

V_{app} is the applied voltage across the sample.

t is the thickness of the sample containing the void.

t_1 is the thickness of the void.

From equation (12), void inception voltage for the samples can be calculated as:

Sample1:

$$V_v = \frac{3000}{[1 + \frac{7,8 - 4,6}{2,3(4.6)}]}$$

$$= 2,303 \text{ kV}$$

Sample2:

$$V_v = \frac{3000}{[1 + \frac{11 - 6,4}{2,5(6,4)}]}$$

= 2,3 kV

Sample3:

$$V_v = \frac{3000}{[1+\frac{11-4,6}{2,3(4,6)}]}$$

= 1,87 kV

The results of the calculated values are compared with the measured values and are presented in Table 6.

Table 6: Values of PD inception voltage

	Measured	**Calculated**
Sample 1	2,4 kV	2,3 kV
Sample 2	2,3 kV	2,3 kV
Sample 3	1,8 kV	1,87 kV

Comparing the measured PDIV with the calculated PDIV, it is noticeable that the values were almost equal which implies that PDIV can be predicted theoretically.

4.7 PD MEASUREMENT ON AN 11 kV VOLTAGE TRANSFORMER

The main aim of this test is to further check the effectiveness and the reliability of using the PRPD pattern diagnostic system to evaluate partial discharge signals in high voltage transformers. For this reasons the PD magnitude was not the most important parameter to consider. An 11 kV voltage transformer made of epoxy resin insulation, which has partial discharge activities, was investigated under different connections as an attempt to identify the type of partial discharges occurring.

4.7.1 Measurement with both HV terminals connected to coupling capacitor (*Cc*) and LV terminals grounded

The circuit arrangement shown in Figure 14 consists of an HV power supply, the test object, the coupling capacitor (*Cc*), the measuring impedance (*Zm*), and the partial discharge measuring device, which consists of the ICM monitor and a personal computer with ICM software to evaluate and save the data.

The HV side of the voltage transformer was connected to the coupling capacitor (*Cc*) and energised. The LV side and the insulation were grounded in an attempt to measure partial discharge activity and also to identify the type of partial discharge taking place. The partial discharge patterns measured at 10 kV are shown in Figure 15.
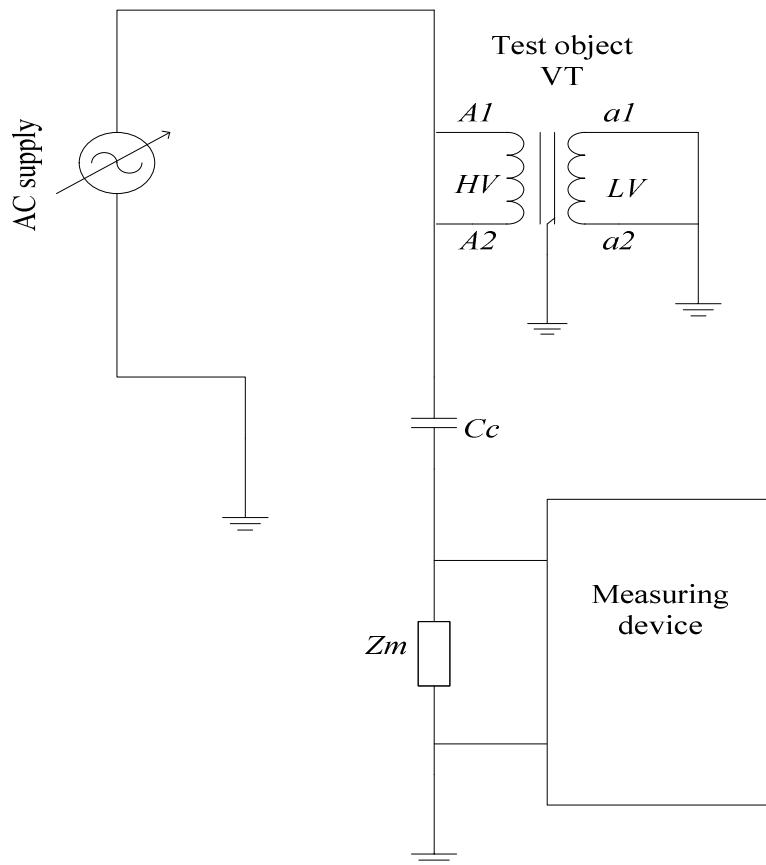
Figure 14: Measuring circuit with both HV terminals connected to *Cc* and LV terminals grounded
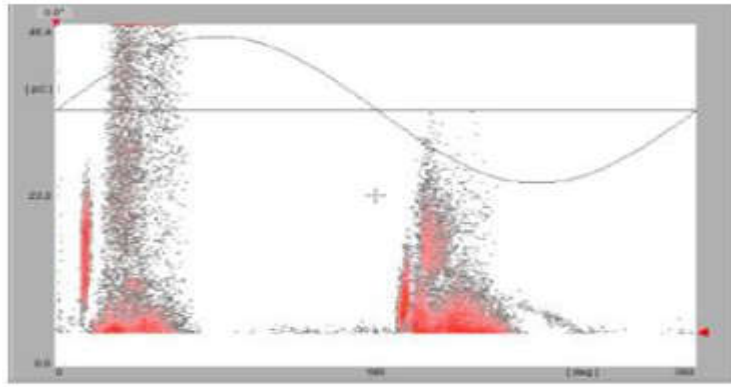
46,4 pC at 10 kV

Figure 15: PRPD pattern measured on an 11 kV VT

Figure 15 shows PRPD patterns of cavity discharge in the insulation of the high voltage winding when the low voltage winding and core are grounded and HV sides are connected to the coupling capacitor as shown in Figure 14. When the applied voltage is higher, the numbers of partial discharges per cycle, the total charge per cycle and the maximum magnitude of the cavity discharge are higher.

When the applied voltage is increased, the maximum discharge magnitude is larger because the maximum electric field in the cavity is higher. At higher applied voltage, the electric field in the void increases faster towards the inception field. This results in more discharges in one applied voltage cycle. When the void is located in the middle of the material, the electric field on the surface of the void is symmetrical, the discharge patterns of cavity discharge at positive, and negative cycles of the applied voltage are also symmetrical (Illias, Yuan, Bakar, Abu, Mokhlis, Chen, & Lewin 2012).

4.7.2   Measurement with one terminal of HV connected to Cc and one of the LV terminals grounded

The circuit diagram used is shown in 16. Figure 17 shows the resulting phase-resolved partial discharge patterns when one side of the HV is connected to the coupling capacitor (*Cc*) and one side of the LV side is grounded. The voltage was

raised below the knee point voltage of 12 kV, as well as above the knee point voltage. The measurements were performed over 60 seconds and the partial discharge magnitudes were recorded.
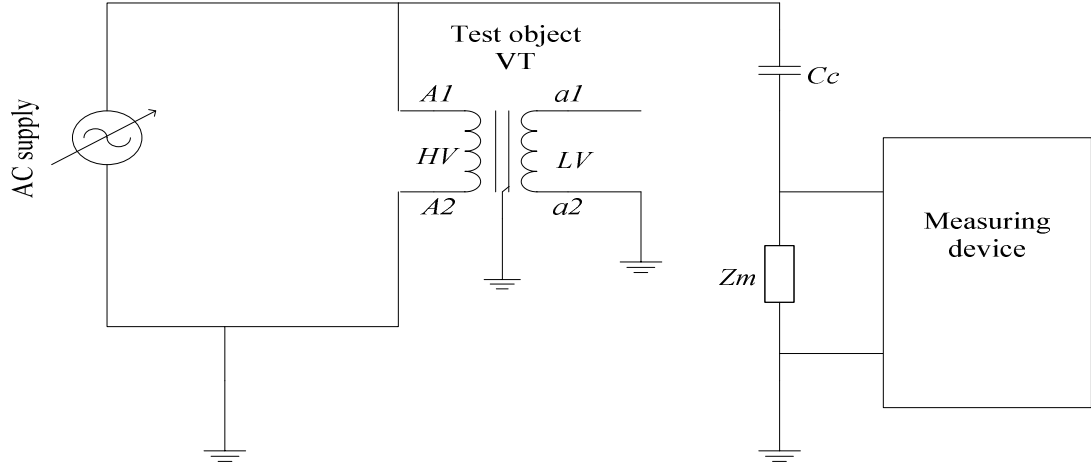
Figure 16: Measuring circuit with one terminal of HV connected to Cc and one LV terminal grounded
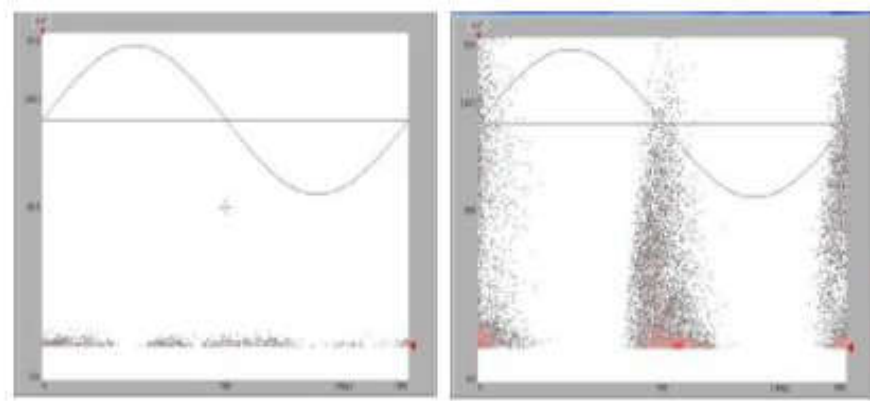
(a) 5.2 pC at 10 kV   (b) 410.4 pC at 15 kV

Figure 17: Partial discharge pattern measured on an 11 kV VT

Figure 17 shows the discharge patterns when the transformer was excited from the high voltage winding as shown in Figure 16. There were no significant discharges

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recorded below the knee-point voltage of 12 kV as shown in Figure 17(a). Partial discharge activities were only recorded above the knee-point voltage as shown in Figure 17(b). The discharges occurred at the zero crossings of the applied voltage. One of the possible reasons for the discharges only occurring above the knee-point voltage can be the distortion of the induced voltage when the core is saturated. The peak of the distorted induced voltage will increase as the core goes deeper into saturation. The PRPD pattern seen also indicates that the discharges are not due to a cavity in the insulation but can rather be attributed to surface discharges (Illias *et al*. 2012).

The reason why the discharges occurring when the connections shown in Figure 14 did not appear during the second test (Figure 16) can be that the defect is in the high voltage insulation at the end of the winding connected to earth. Therefore, the defect was not stressed enough for discharges to occur (Illias *et al*. 2012).

4.7.3 Measurement with other terminal of HV connected to Cc and one terminal of the LV grounded

Figure 18 shows the measuring circuit diagram. Figure 19 shows the results of PRPD patterns recorded over 60 seconds of measurement. One side of the HV of an 11 kV voltage transformer was connected to the coupling capacitor (*Cc*), whilst the other side of the LV remained grounded.
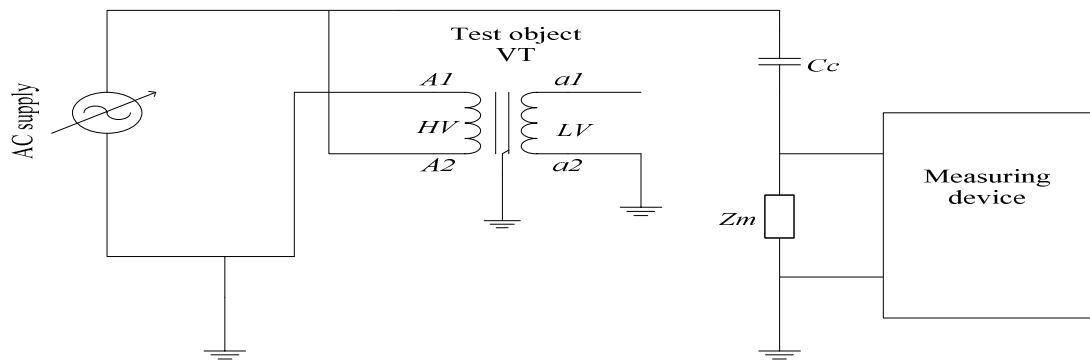
Figure 18: Measuring circuit with one side of HV connected to the *Cc* and one side of the LV grounded
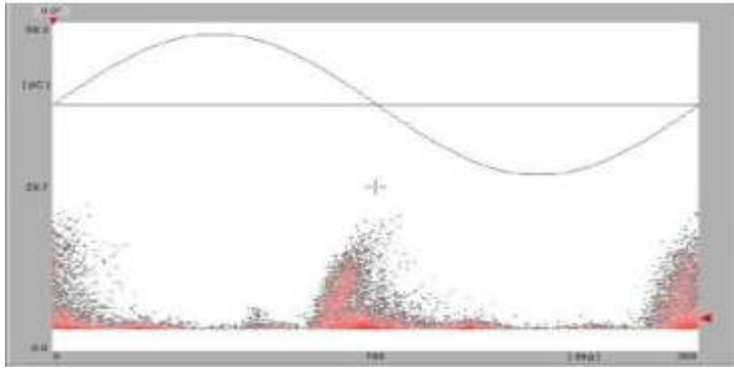
21.2 pC at 15 kV

Figure19: Partial discharge pattern measured on an 11 kV VT

Comparing the patterns in Figure 19 with that of table 5 sample 2 it can be seen that the partial discharge patterns indicate the cavity between the insulation of the high voltage side and the earth. Partial discharges occur on both positive and negative half cycles and 21.2 pC of the maximum partial discharge was recorded.

4.8   PARTIAL DISCHARGE MEASUREMENT ON 300 kV TRANSFORMER

In this section, reporting is done on phase-resolved partial discharge measurement results obtained on the 400 V/300 000 V single-phase transformer. Due to the limitation of the coupling capacitor PD evaluation was only done up to the maximum voltage of 200 kV.

4.8.1   Phase-resolved partial discharge measurements

Various sets of phase-resolved patterns were obtained in this study. The measurements are carried out by varying the voltage to different levels. The phase-resolved plot displays all discharge pulses obtained during 60-second intervals at different magnitudes of applied voltages.

The horizontal axis is the phase angle where partial discharge pulses occurred while vertical axis is the partial discharge charge magnitude in pC. Each point has a colour, which represents the number of partial discharges that occurred with given amplitude and phase (a brighter colour indicates a higher number) (Conti 2003). Partial discharge magnitude increases with the applied voltage.

4.8.2   Preliminary observations for partial discharge detection

Figure 20 shows the background noise recorded at the initial stage when the system was energised for the first time. The magnitude was recorded as 5,21 pC and Figure 12 shows the measuring circuit used.
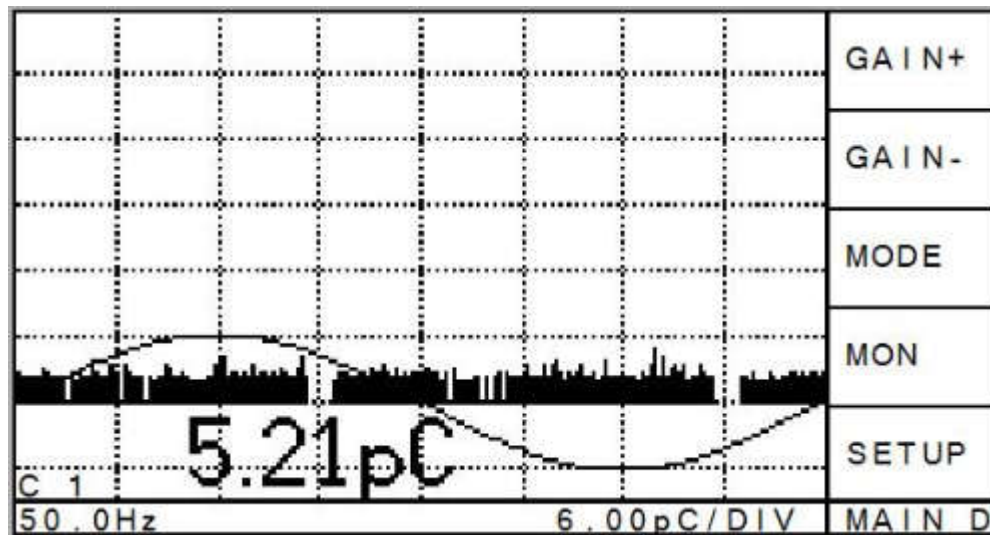
Figure 20: Noise recorded initially

To reduce the noise level, a screened isolator transformer was connected to the low voltage side of the test system. An isolation transformer provides a barrier to high frequency noise when coupled with a suitably grounded and prevent propagation of this noise to the down stream equipment via the power supply or ground system. As illustrated in Figure 21, a shielded isolation transformer provides a path for high frequency common mode noise to flow via capacitive coupling to the grounded screen (ERICO).
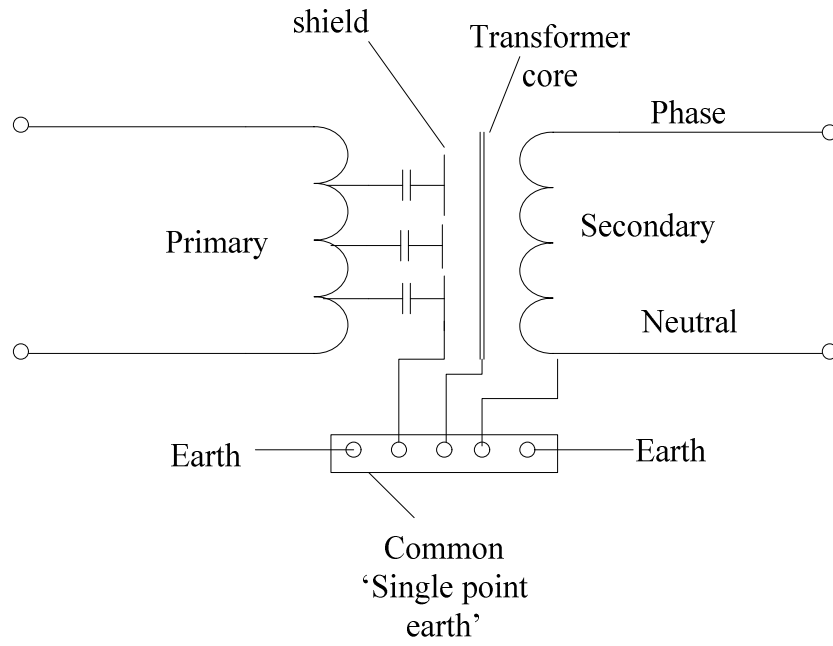
Figure 21: Schematic diagram of Isolation transformer (ERICO)

Figure 22 shows the circuit diagram of the screen isolator transformer connected to the measuring device. The background noise drastically reduced from 5,21 pC to 1,27 pC as shown in Figure 23.
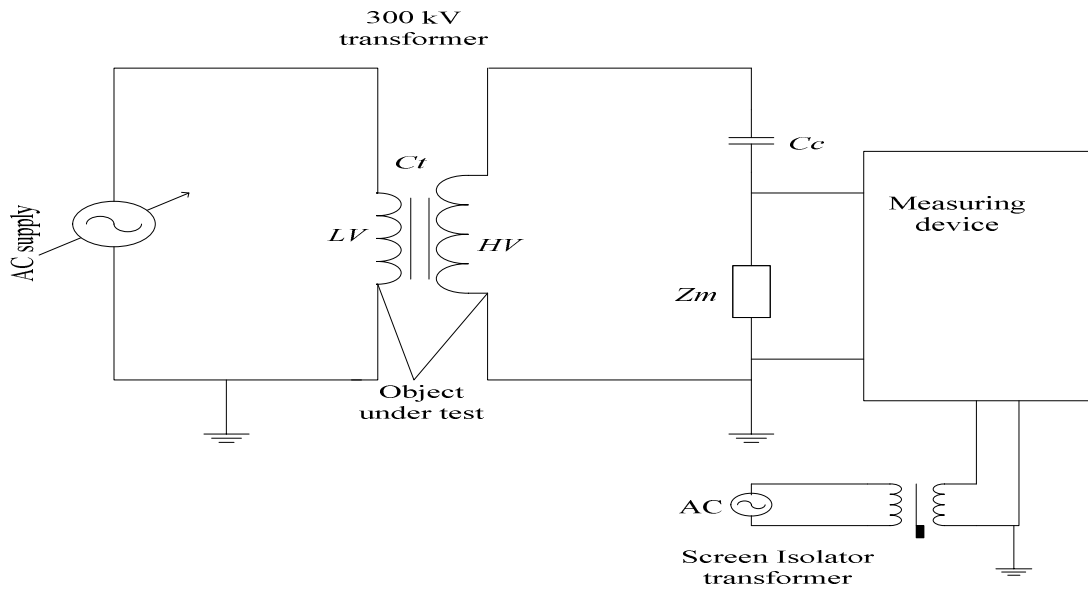
Figure 22: Circuit diagram of the test set up
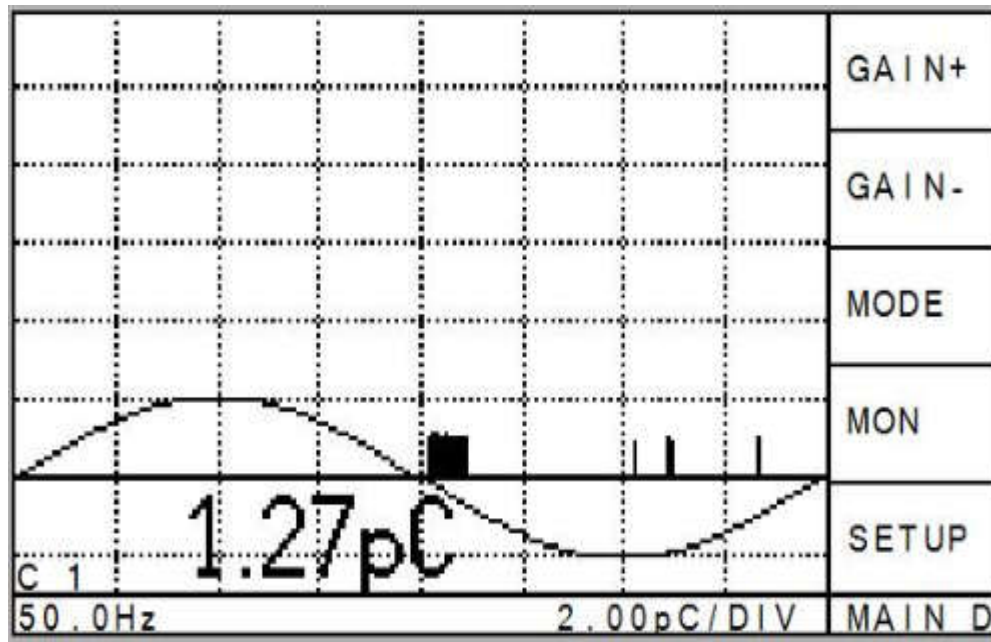
Figure 23: Background noise recorded after the isolator transformer was connected

4.8.3   Partial discharge measurement using a 1 nF, 100 kV coupling capacitor (*C1*)

Figure 12 is the laboratory arrangement for the setup. Figure 24 shows the photograph of the set up. Figure 25 shows the typical phase to number (*Φ-q*) patterns for the 300 kV transformer.

The figure clearly shows that partial discharge occurrence is strongly dependent on the instantaneous value of the applied voltage. Therefore, the shape of the partial discharge pulse distribution in phase angle fits well with the shape of the applied voltage as reported by Suwarno and Sutikno (2011).
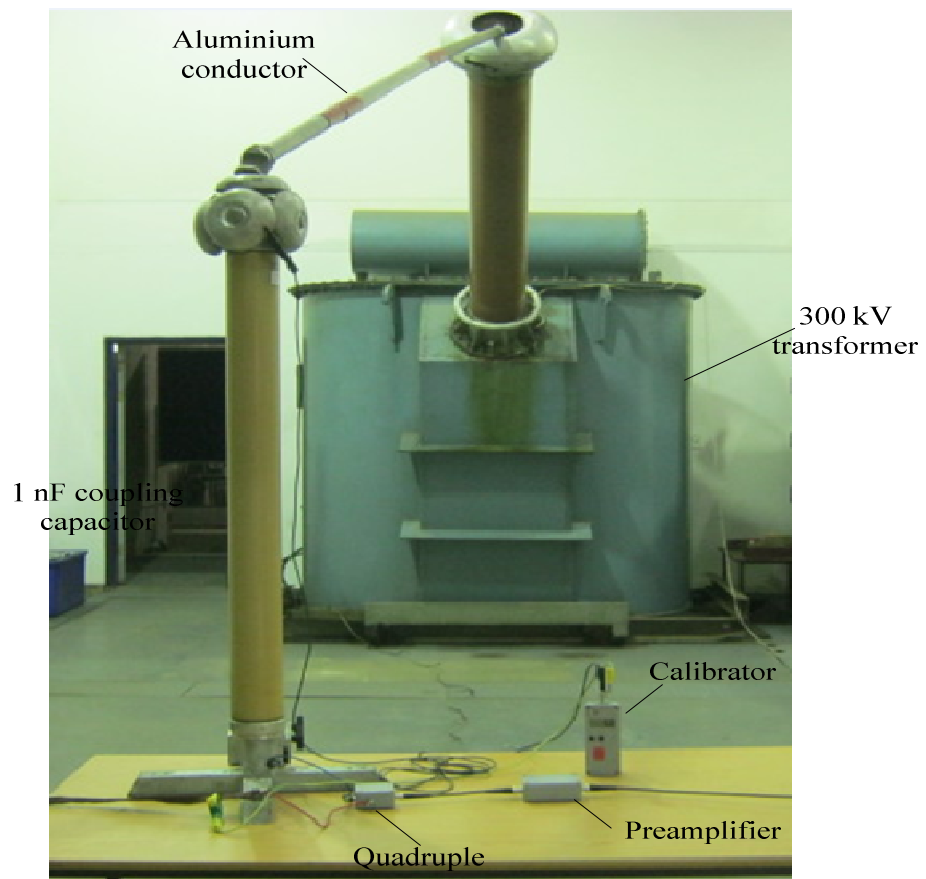
Figure 24: A photograph of the laboratory setup
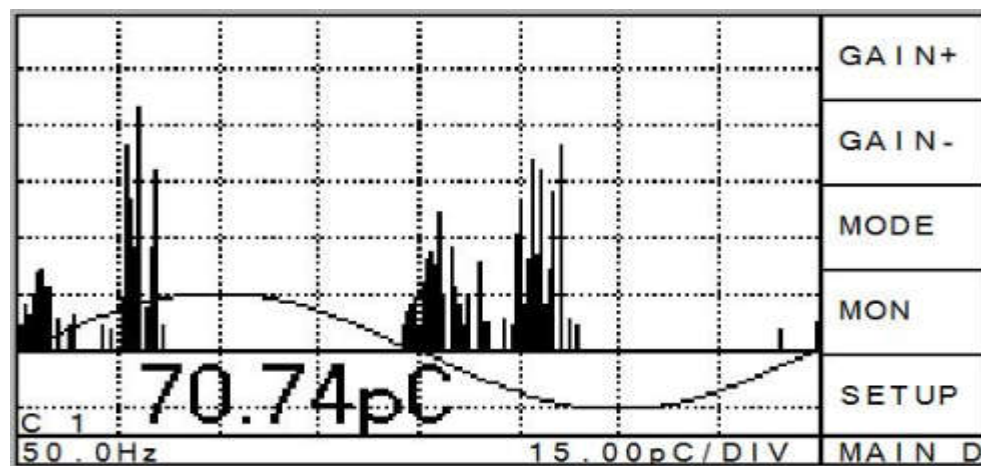
70,74 pC at 70 kV

Figure 25: Typical *Φ-q* patterns for a 300 kV transformer
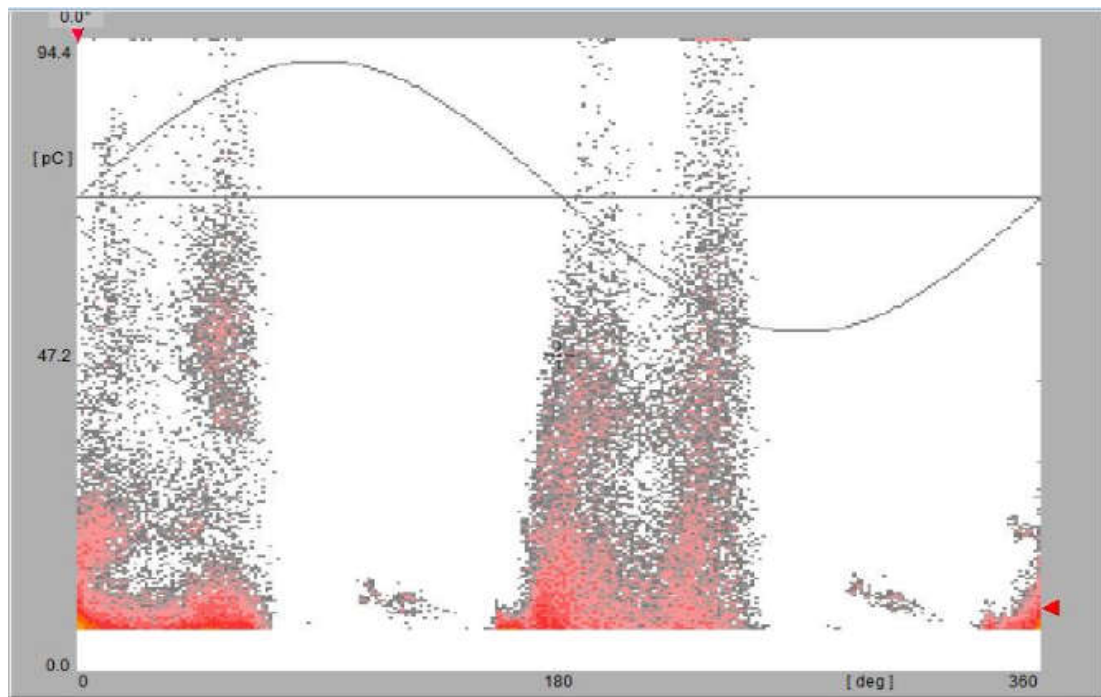
70,74 pC at 70 kV

Figure 26: Typical phase resolved PD pattern for 300 kV HV transformer

The phase-resolved patterns obtained from a partial discharge measurement performed on a 300 kV HV transformer is shown in Figure 26. This phase-resolved plot displays all discharge pulses obtained during 60 seconds. The horizontal axis is the phase angle where partial-discharge pulses occurred while vertical axis is the partial-discharge charge magnitude in pC. Each point represents a partial-discharge charge and the position indicates the partial-discharge magnitude and phase angle where the partial discharge takes place. The partial-discharge magnitude increases with the applied voltage. Partial discharge pulses were observed in both polarities under voltage rise and fall.

Comparing Figure 26 with that of Figure 17(b) and Figure 15, it is seen that the patterns appear to be both internal discharges and surface discharges. At higher voltage, another pattern appears which indicate surface discharges. After inspection,

it became clear that these partial discharges are caused by improper connections of the measuring system and the ground wire. Improper grounding close to the high voltage could cause the concentrations of fields around the edges of the circuit and if the electric field is sufficiently large, it can produce discharge pulses.

4.8.4 Partial discharge measurement using a 1 nF, 100 kV (C1) coupling capacitor with an improved shielding of the coupling capacitor

Figure 27 shows a photo of the laboratory setup with the coupling capacitor C1 connected to the transformer indicating where it was shield. Figure 28 shows the partial discharge pulses recorded from the measurement on a 300 kV transformer. Figure 29 presents the PRPD patterns measured on a 300 kV transformer.
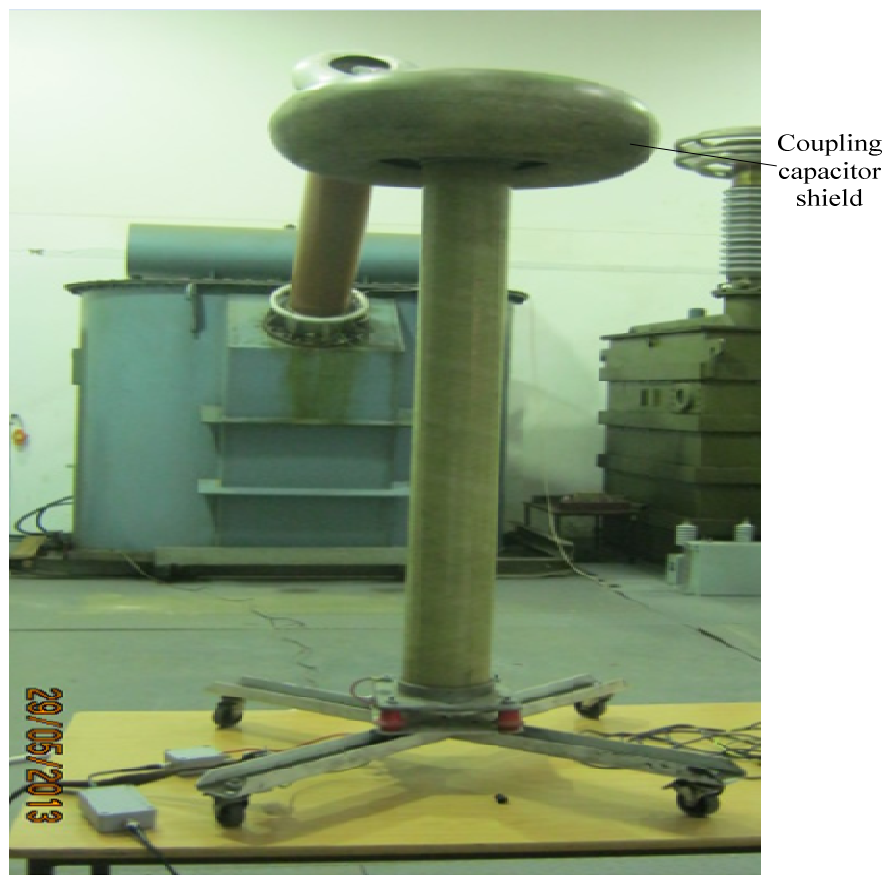
Figure 27: A photograph of the shielded coupling capacitor
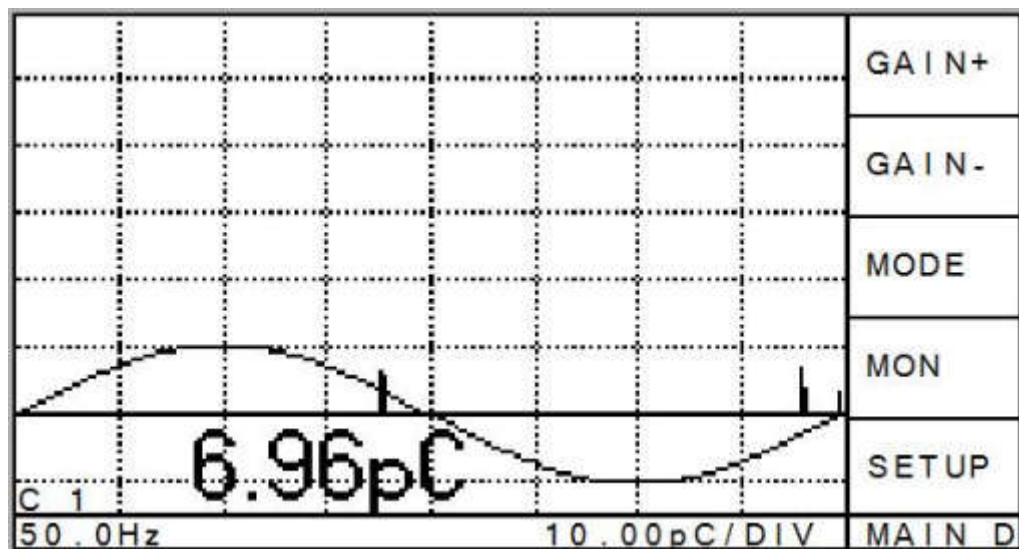
6,96pC at 70 kV

Figure 28: Partial discharge pulses recorded from the measurement of a 300 kV transformer
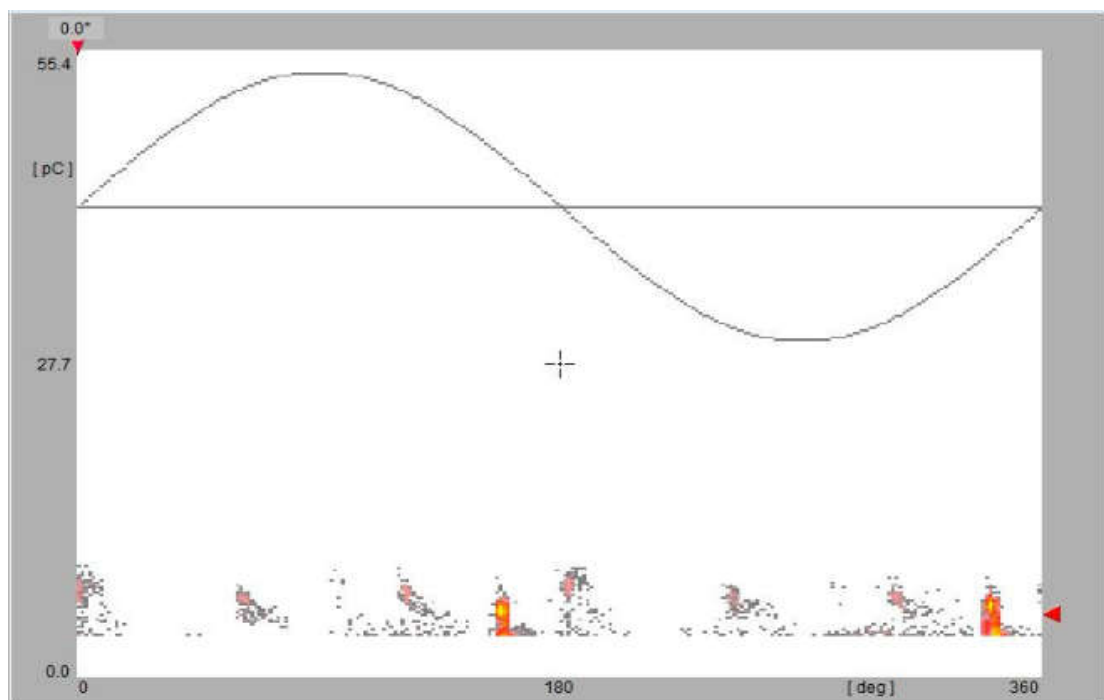
6,96 pC at 70 kV

**Figure 29:** PRPD pattern measured on a 300kV transformer

Comparing Figure 29 to the pattern in Figure 26, it is clear that the PD pattern has reduced to 6,96 pC at 70 kV. After inspection it was observed that these discharges occurred because the connection point on top of the shielded coupling capacitor from which the conductor is connected was loose. When there is a loose connection the electrode creates a local electric field build up which results in partial discharges.

4.8.5   Partial discharge measurement using 500 pF, 200 kV coupling capacitor (C1+C2)

The setup was rearranged and two 100 kV, 1 nF coupling capacitors were used conjointly as a 500 pF (200 kV) coupling capacitor. The aluminium conductor was used to connect from the bushing of the transformer to the sphere connector hanging at the end of the insulator. Then, another aluminium conductor was connected from there to the coupling capacitor. The system was calibrated with 5 pC. Figure 30 shows the circuit diagram and Figure 31 is the photograph of the new arrangement with the 500pF coupling capacitor.
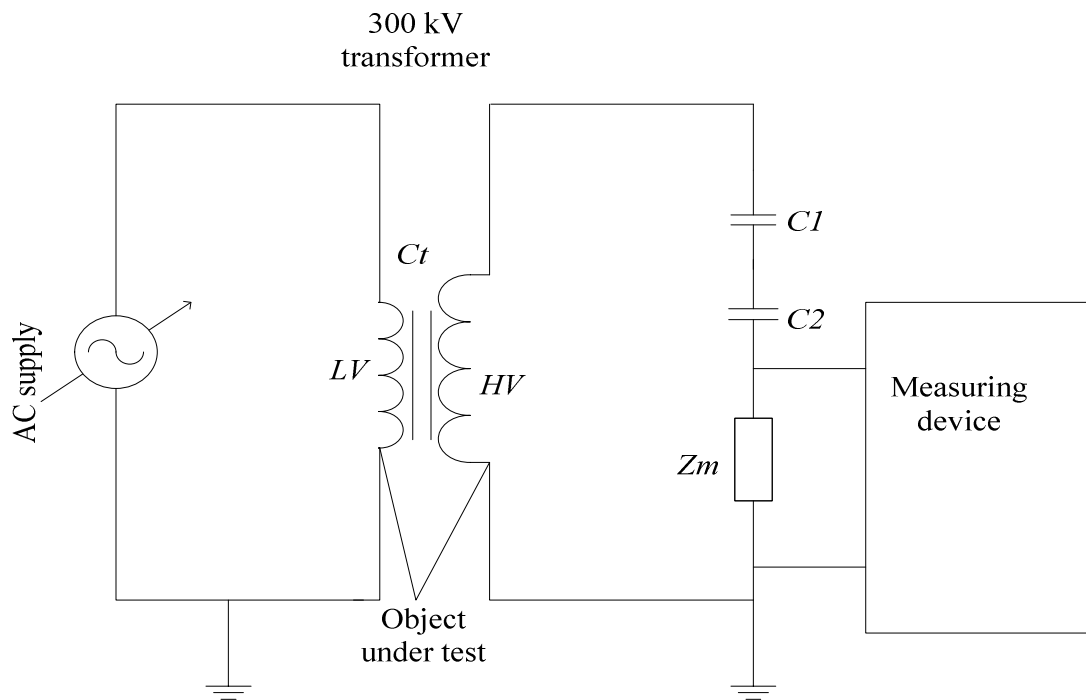
Figure 30: Measuring circuit diagram with a 500 pF Coupling capacitor

Figure 31: Laboratory arrangement of the measuring circuit

The setup was energised and the voltage was increased in steps from 10 kV to 150 kV. Nothing recorded at this stage. The aim was to check the setup to see if the connections were done properly. The voltage was then raised further above 150 kV and continuous corona discharges occurred, which resulted in arcing from the sphere connector. Figure 32 shows the arcs from the sphere.
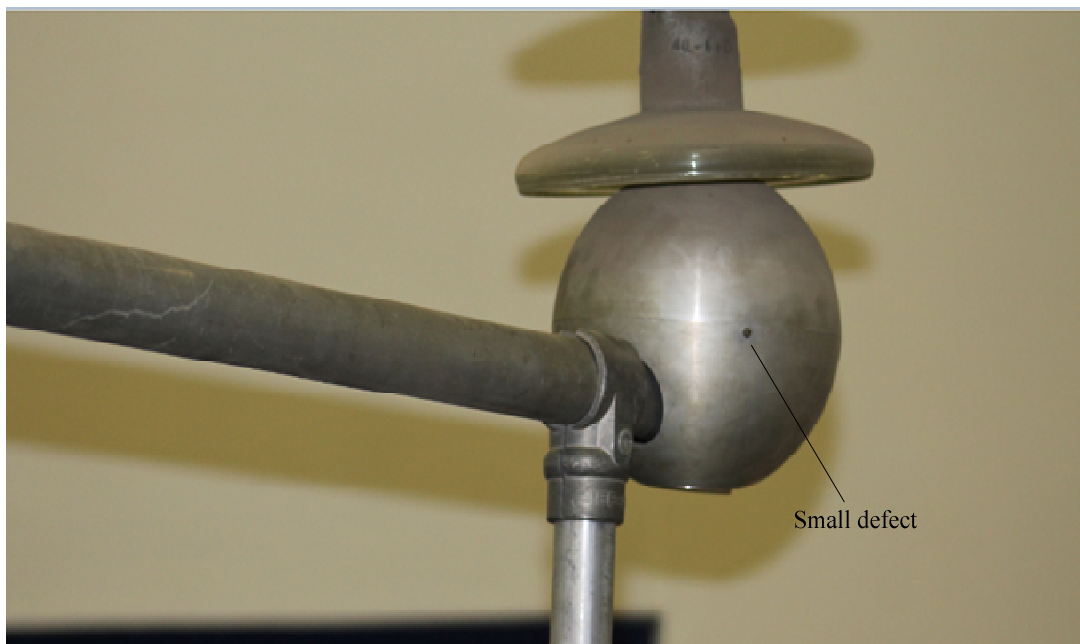
(a)

(b)
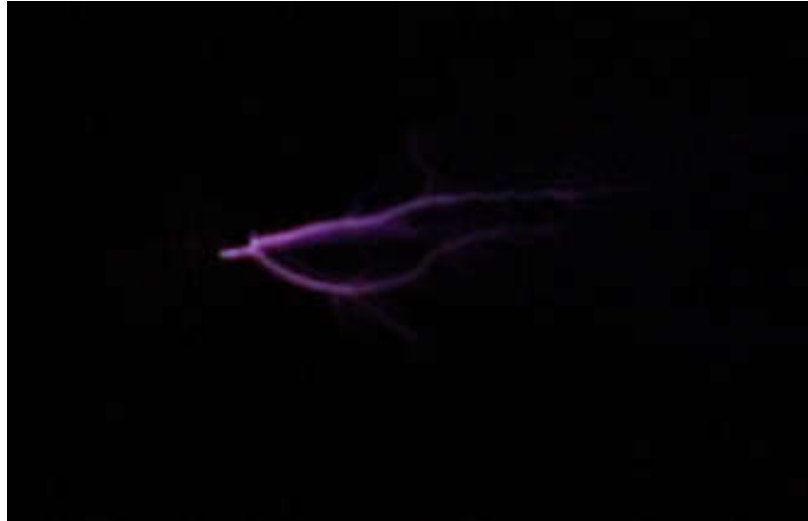
(c)

Figure 32: (a) Aluminium sphere with small defect and (b) the arc from the defect on the sphere (c) The arc

Since a 300 kV coupling capacitor was not available, two 100 kV coupling capacitors were used as a 500 pF (200 kV) coupling capacitor as shown in Figure 30. After checking if the connection was properly done, the applied voltage was increased from 10 kV to 150 kV and no noise or corona was heard. The voltage increased further above 150 kV and continuous corona discharges occurred, which resulted in arcing from the aluminium sphere as shown in Figure 32.

The setup was rearranged with the aluminium conductor connected from the bushing directly to the 500 pF coupling capacitor as shown in Figure 33. The system was energised and the voltage was then increased in steps from 10 kV to 200 kV.

Figure 34 shows different types of partial discharge pulses recorded from the system. Figure 35 shows partial discharge patterns at different voltage levels applied to the transformer.
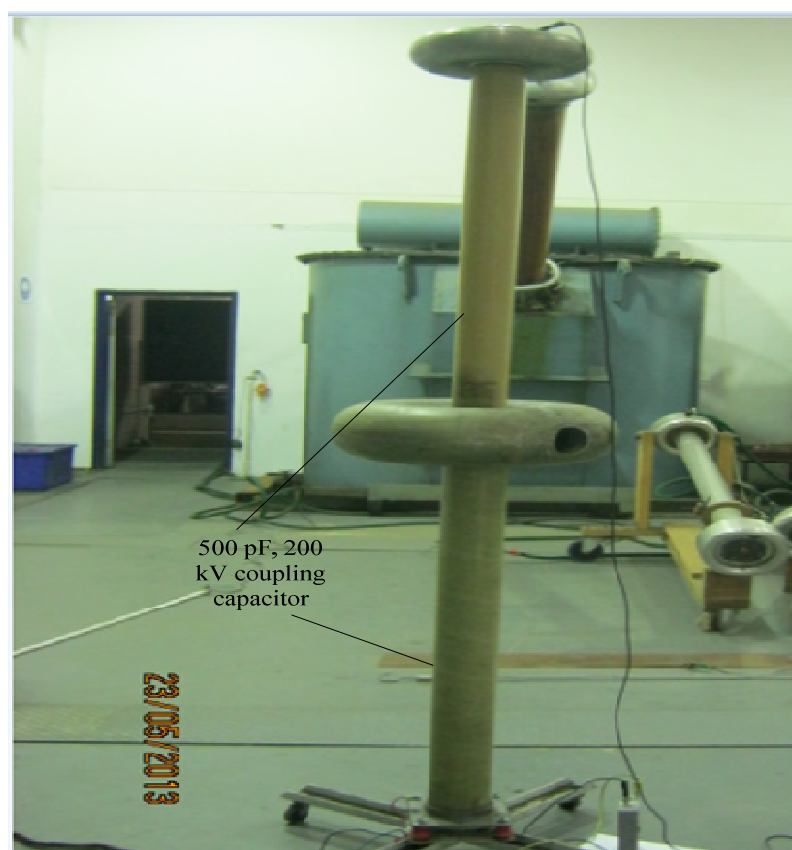
Figure 33: Laboratory photograph of the new arrangement
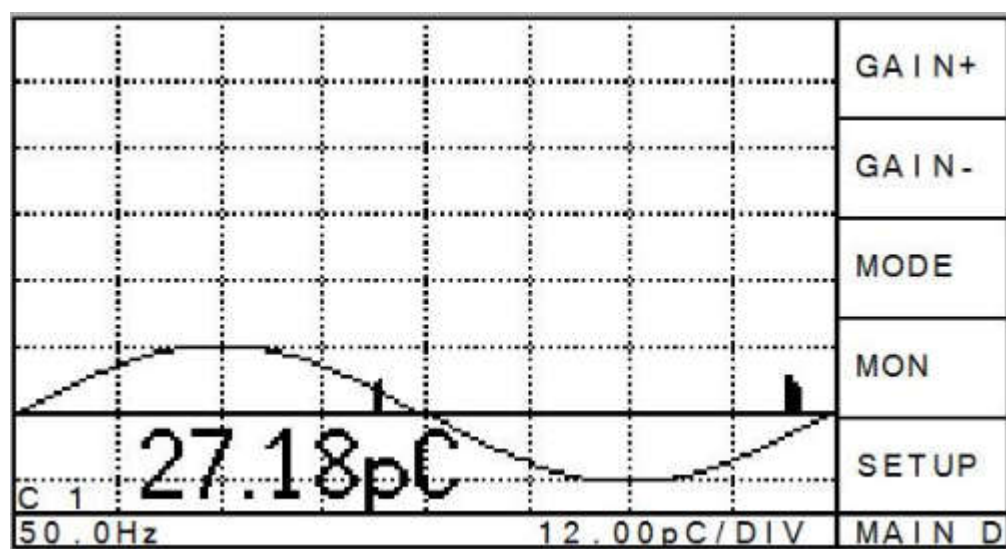
(a) 27,18pC at 190 kV
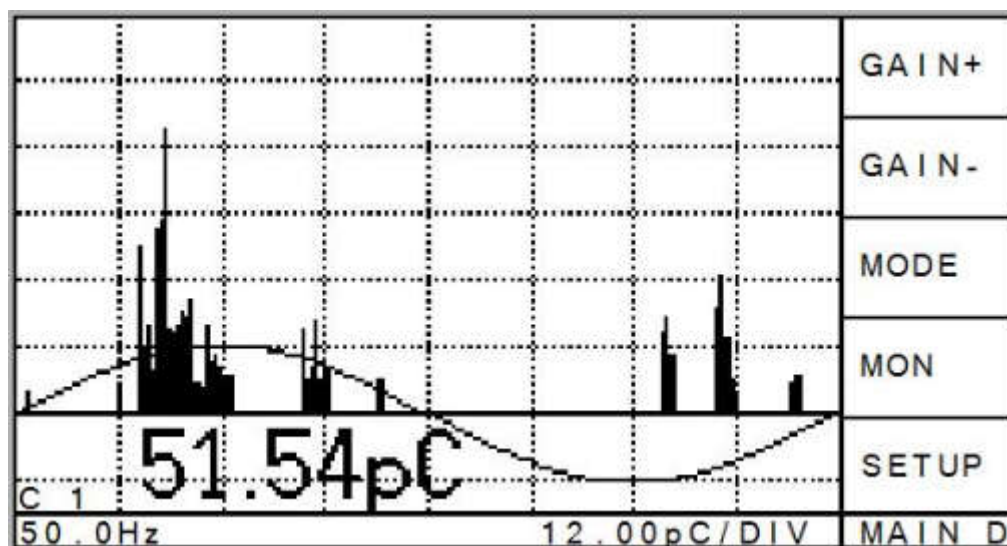
(b) 51,54pC at 200 kV

Figure 34: Partial discharge pulses recorded from the measurement on a 300 kV transformer
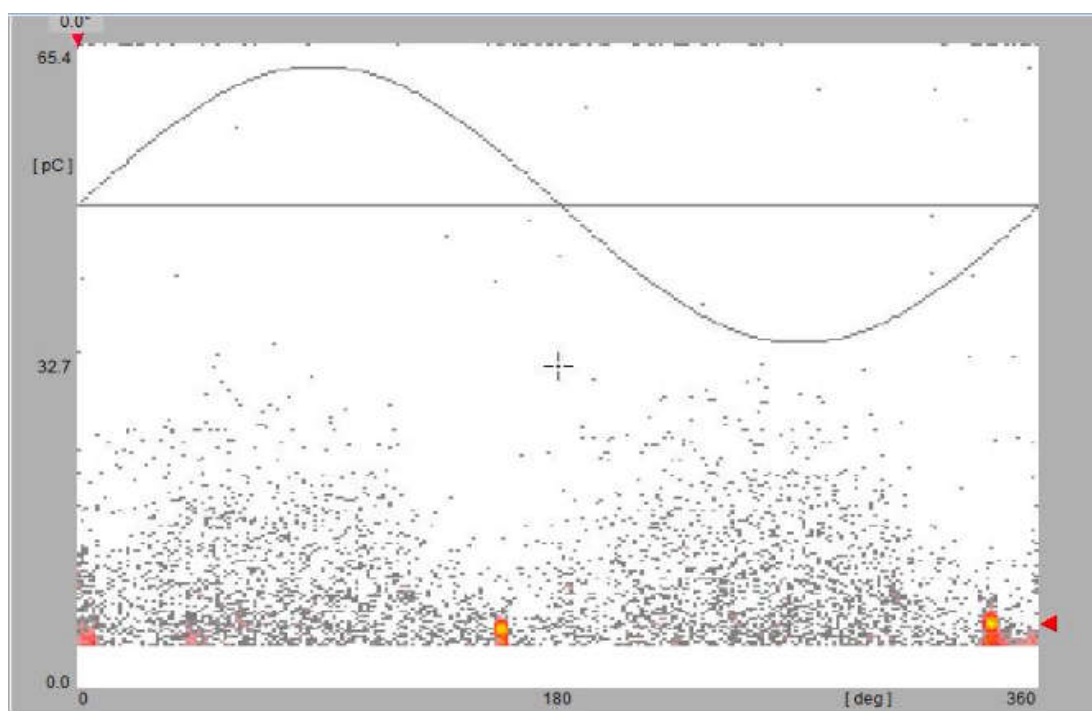
(a) 27,18pC at 190 kV
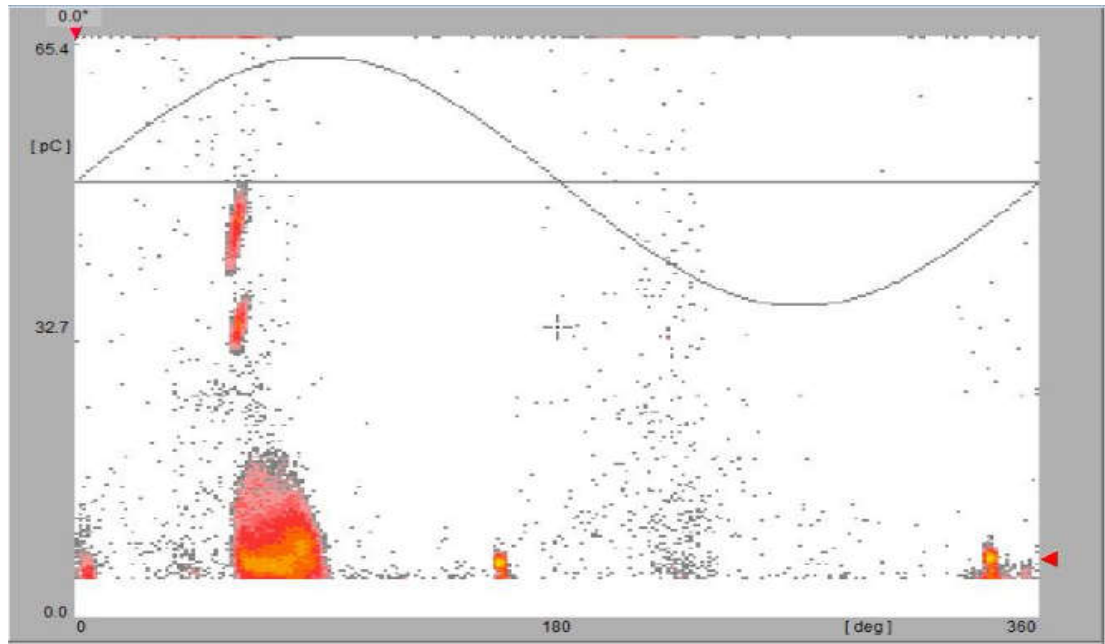
(b) 51,54pC at 200 kV

Figure 35: PRPD pattern measured on a 300kV transformer

Referring to Figure 35(a), it is clear that at 190 kV, there are no significant discharges in both cycles but it appears at 200 kV on the positive half cycle as shown in Figure 35(b). At lower applied voltage, the probability of getting an initial free electron due to the negative electrode to start an ionisation is low. Thus, lower discharge occurs at the negative cycle. There are many discharges occurring at the positive half cycles because electrons are readily available from the positive polarity electrode to ionise the surrounding neutral gas molecules in order to generate avalanches. Therefore, the patterns of corona discharges at positive cycles of the applied voltage are not symmetrical (Illias *et al*. 2012). Moreover, that 51,54 pC recorded can be attributed to the coupling capacitor stressed up to the maximum rated value of 200 kV.

4.8.6 Partial discharge measurement using CT1

CT1 is a high frequency current transformer with a window of 15 mm and is a fixed installation as the earth lead must be threaded through the window. CT1 has a -3 dB bandwidth of 0,5-80 MHz and a -6 dB bandwidth of 0,3-100 MHz. Figure 36 shows the measuring circuit. Figure 37 shows the laboratory arrangement.

The circuit arrangement is the conventional partial discharge test circuit in accordance with IEC 60270. It consists of the HV power supply, the test object Ct, the high frequency current transformer (HFCT), the measuring impedance Zm, and the partial discharge measuring device.

The partial discharge measuring device consists of the ICM monitor and a personal computer with the ICM software used to evaluate and save the data. Figure 38 shows the partial discharge pulses recorded from the 300kV transformers. The PRPD patterns obtained from the measurements are presented in Figure 39.
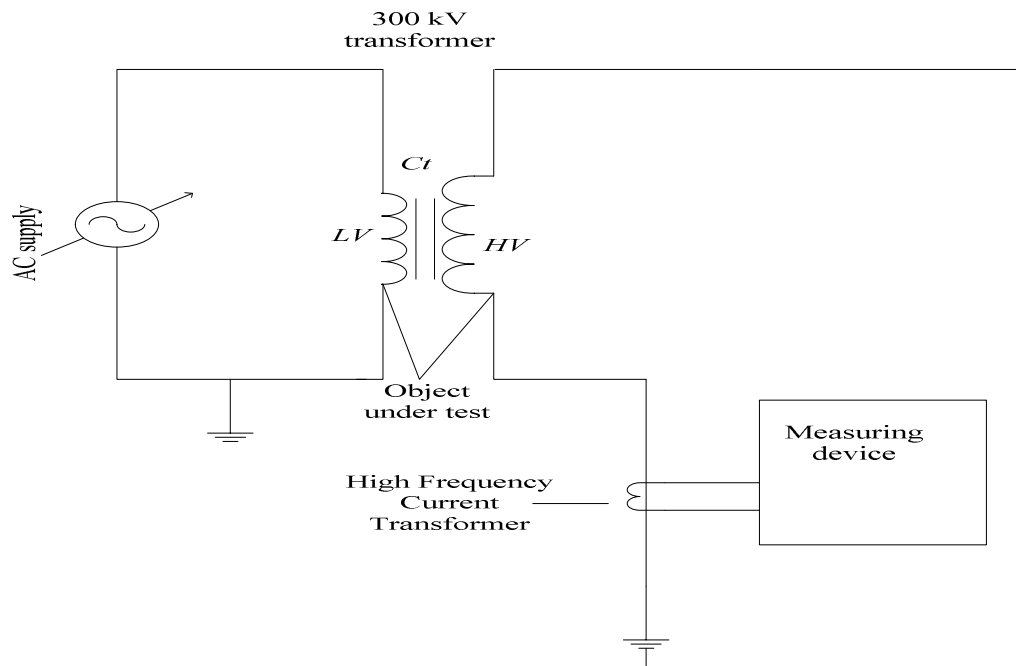
Figure 36: The measuring circuit with CT1
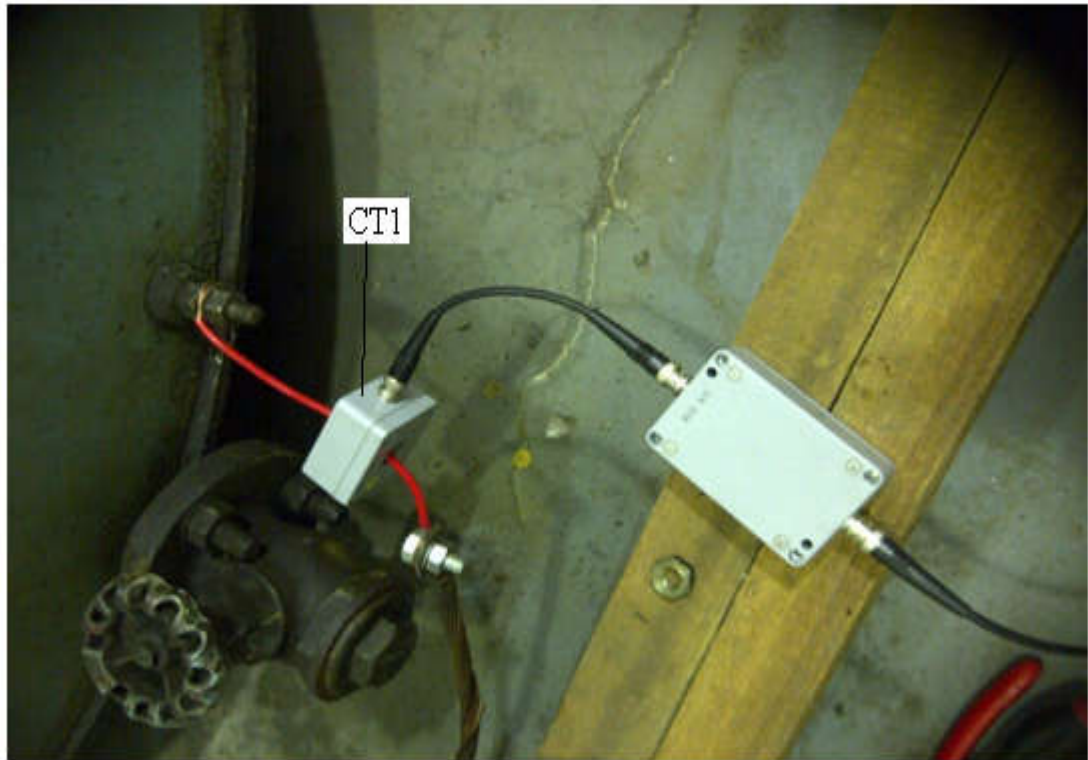
Figure 37: A photograph of the laboratory arrangement with CT1
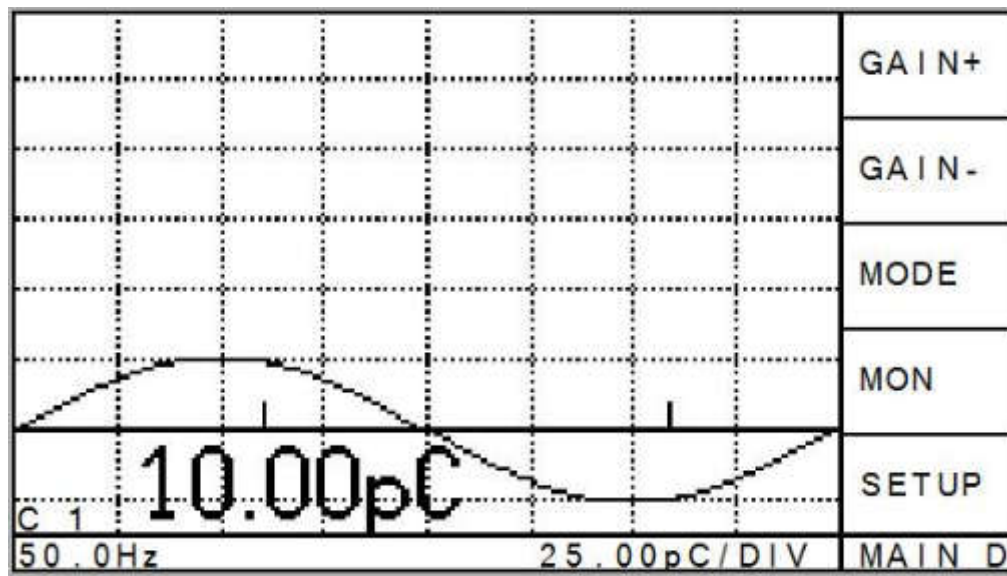
(a) 10,00 pC at 200 kV
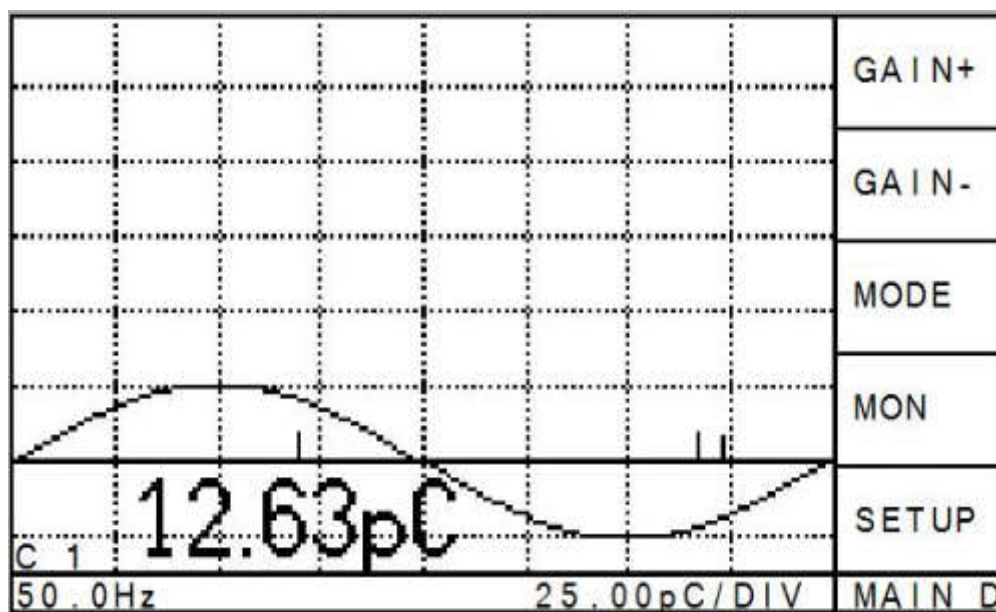
(b) 12,63 pC at 250 kV

Figure 38: Partial discharge pulses recorded from a 300kV transformer
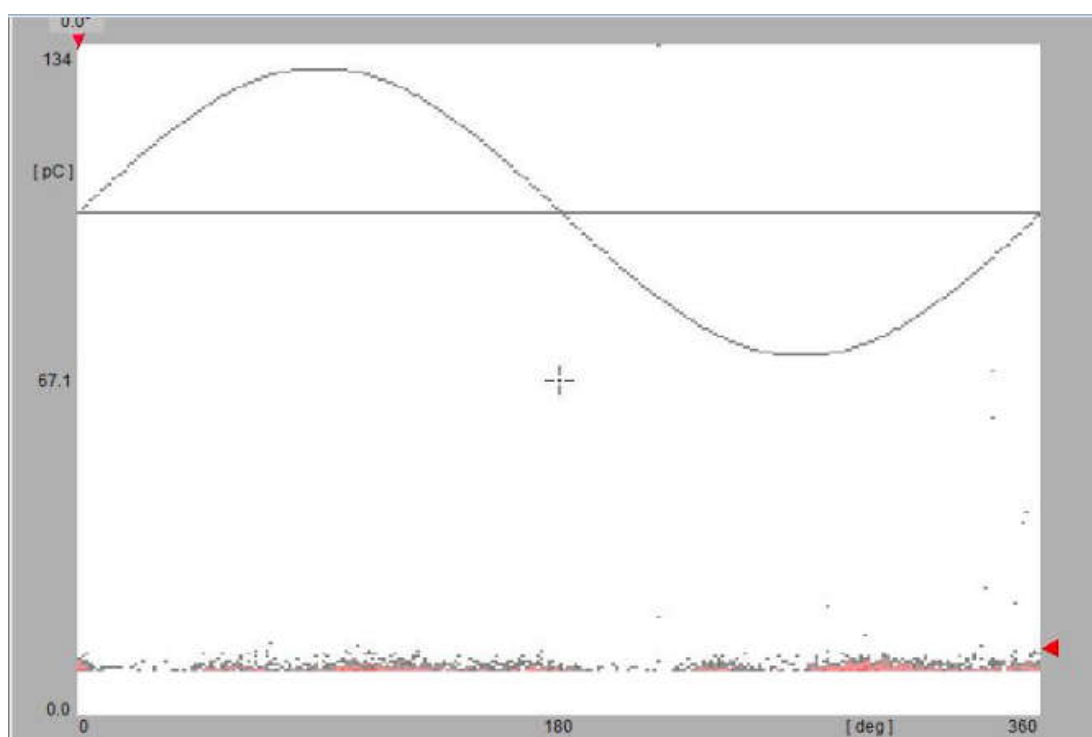
(a) 10,00 pC at 200 kV
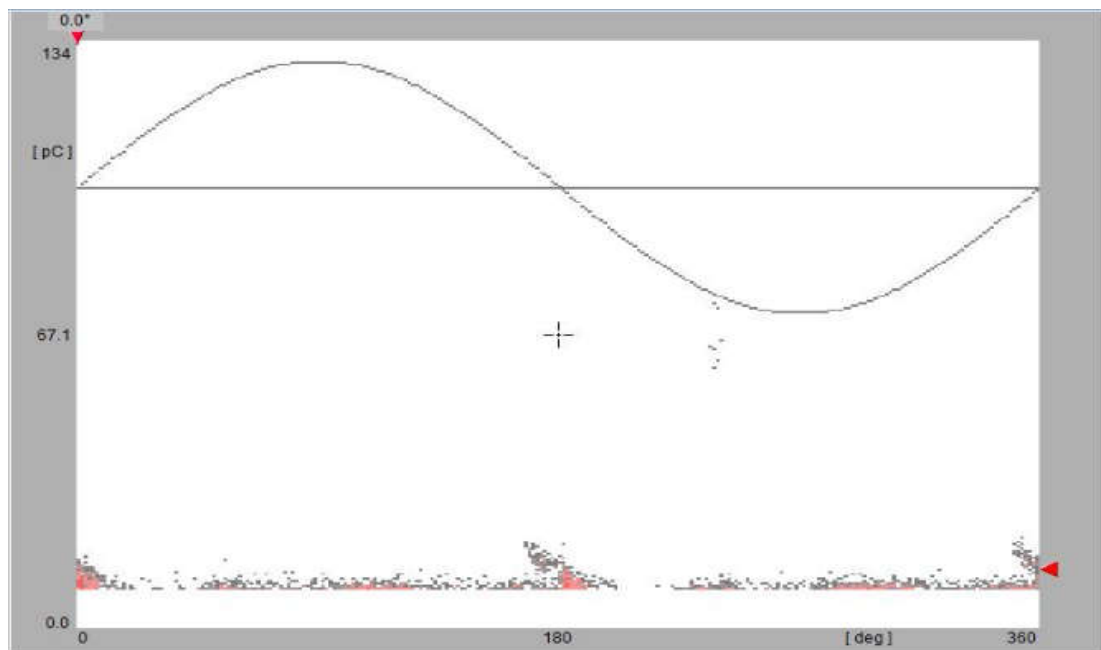
(b) 12,63 pC at 250 kV

Figure 39: PRPD pattern measured on a 300 kV transformer with CT1

4.8.7   Partial discharge measurement using CT100

High frequency CT100 is a clamp-on current transformer with a window of 100 mm, which is placed around the earth lead.

CT100, therefore, can be applied without any disconnection of earth leads or interruption of the supply. It has a -3 dB bandwidth of 2 – 25 MHz and a -6 dB bandwidth of 1.2 – 40 MHz.

Figure 40 shows the laboratory arrangement of the measuring setup. Figure 41 shows the partial discharge pulses measured from a 300 kV transformer. Figure 42 presents the patterns obtained from the transformer.

Figure 40: A photograph of the laboratory setup with CT100
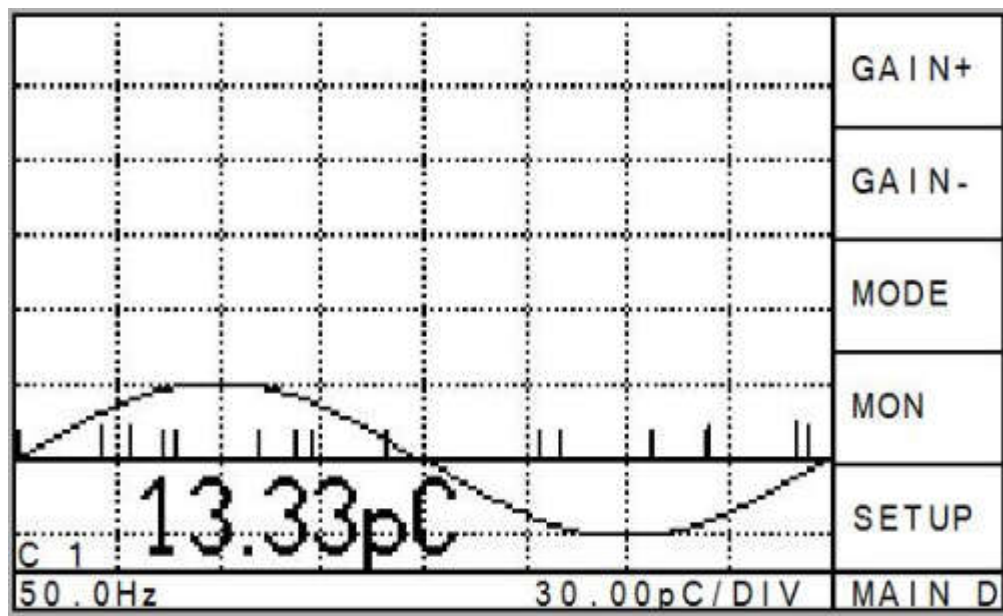
(a) 13,33 pC at 200 kV
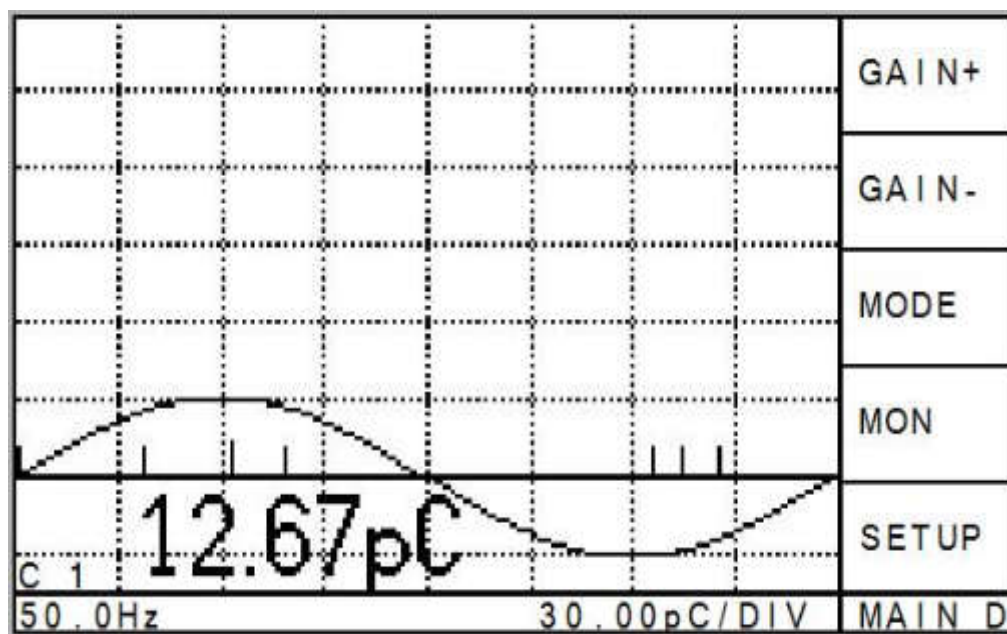
(b) 1267 pC at 250 kV

Figure 41: Partial discharge pulses recorded from a 300kV transformer
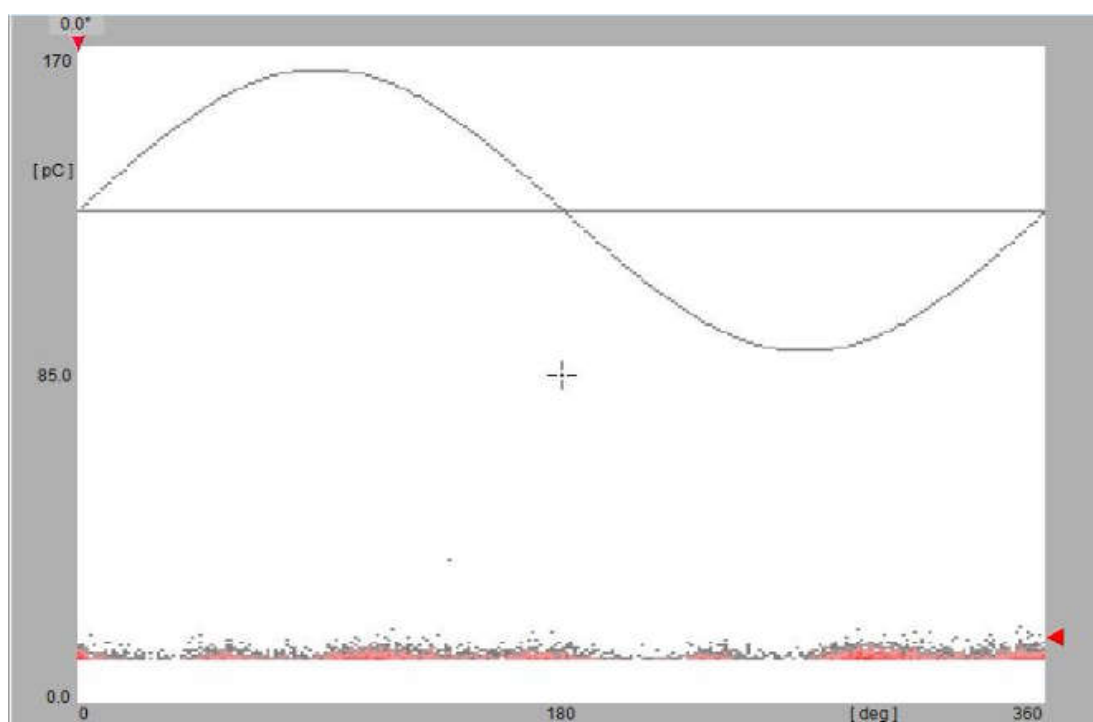
(a)   13,33 pC at 200 kV
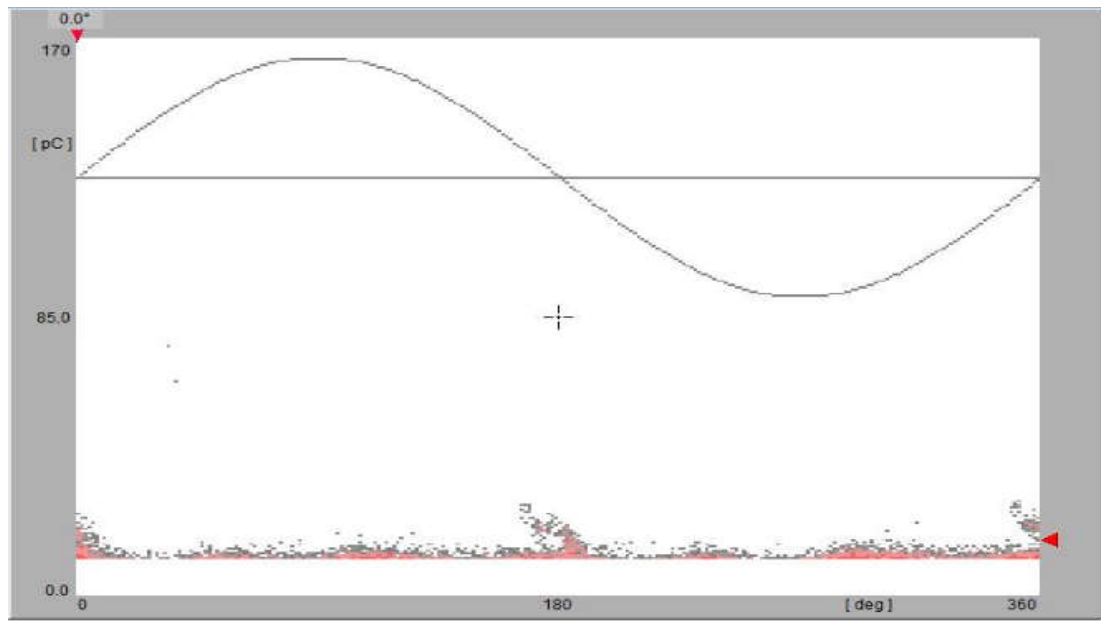
(b) 12,67 pC at 250 kV

Figure 42: PRPD pattern measured on a 300 kV transformer with CT100

High frequency current transformer (HFCTs) sensors detected partial discharge signals as shown in Figure 39 and Figure 42. Comparing both figures, it shows that the patterns are similar and small signals detected. The partial discharge magnitude recorded in the transformer using HFCTs were 12,63 pC from CT1 and 12,67 pC from CT100 at 250 kV.

The experimental results obtained from the phase-resolved partial discharge measurements on the 400 V/300 000 V single-phase transformer were presented. After various tests on the transformer, it has established that, the 300 kV transformer did not exhibit any signs of partial discharge which could hamper its operations. In addition to that, the insulation of the transformer is healthy and therefore, can operate up to its full capacity.

4.9   SUMMARY

This chapter explained the experimental setup of a partial discharge measuring circuit according to the South African National Standards (SANS) (SABS 60270) and the International Electrotechnical Commission Publication (SANS & IEC 60270:2000). The chapter also presented the detailed discussion of the results of the experiments conducted on the 11 kV voltage transformer and the 3 test samples. The results obtained have proved the effectiveness and the reliability of the diagnostic method employed in this work. The chapter further reports on phase-resolved partial discharge measurements and the results obtained on the 400 V/300 000 V single-phase transformer.

The next chapter presents the conclusion of the dissertation and the areas for further development and research.

CHAPTER FIVE: CONCLUSION AND RECOMMENDATION

5.1 CONCLUSION

The aim of this research was to assess the condition of a 300 kV transformer that was manufactured in 1967. The researcher's purpose was to find out if there was a partial discharge in the 300 kV transformer. That is because partial discharge is the main cause of breakdown of insulation systems. The researcher therefore intended to examine if the transformer could still operate as effectively as a new transformer despite its old state. In order to fulfil this aim, the researcher used a faulty 11 kV voltage transformer and 3 test samples as samples to verify the effectiveness of the phase-resolved method that was used to examine the 300 kV transformer.

After a proper examination of the 300 kV transformer's insulation using the phase-resolved method, it was determined that the transformer was healthy up to 200 kV and that the users of the transformer can carry out all their necessary experiments effectively. The phase-resolved method was appropriate for the measurements of partial discharge in transformers because it can easily identify the different defects and their locations compared to other methods such as the acoustic method and Dissolved Gas Analysis. After analysis, it was observed that there was an internal discharge in the 11 kV voltage transformer's insulation, causing it to malfunction. Similarly, when analysing the 3 test samples, the location of the partial discharge in the samples were identified.

In light of the above, the pre-existing views concerning the condition of the 300 kV transformer were challenged. In spite of the old age of the transformer, it was still in a good condition and reliable. This means that, as far as a transformer is concerned, age does not really matter. The functioning of a transformer mainly depends on a healthy insulation system.

This dissertation has therefore shed the light on the relation between the age and the good health of a transformer in terms of partial discharge.

Nevertheless, the researcher could not use a 300 kV coupling capacitor because it was not available in the laboratory. That is why a 200 kV coupling capacitor was used throughout the experiments. However, the researcher used a HFCT to complement the 200 kV coupling capacitor.

This dissertation mainly focused on the phase-resolved partial discharge method.

5.2 RECOMMENDATION

The ultimate goals of using power transformer diagnostic technology are to improve the overall reliability of the power distribution network system, reduce maintenance cost and avoid undesirable service failures. Although the research has presented contributions to various areas that are important to reach these goals, there are still several interesting future directions, which could help.

The more important of these directions are:

- The work presented in this research regarding the use of coupling capacitor has only considered 200 kV coupling capacitor. Thus 300 kV coupling capacitor is required to be able to test the transformer up-to the maximum voltage of 300 kV.
- The partial discharge measurement with acoustic method of testing can also be applied to the transformer.

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Session Eleven:

Partial Discharge Evaluation of a High Voltage Transformer

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Abstract

This paper describes the procedures followed to evaluate the condition of the insulation of a 22 kV Voltage transformer (VT) in the High Voltage Laboratory at Vaal University of Technology through measurement of partial discharges. This is the first part of the evaluation of the insulation of the 300 kV transformer in the high voltage laboratory. Two methods were employed in this evaluation to detect the partial discharge signals, namely, the use of Capacitive Coupling by means of a Coupling Capacitor and Inductive Coupling through High Frequency Current Transformers (HFCT's). The partial discharge evaluation methodology followed consists of measurement of the partial discharge magnitude and Phase Resolved Partial Discharge Measurements. The results from the different signal detection methods are compared and discussed.

Keywords: Partial Discharge, Voltage Transformers, high frequency current transformer, Evaluation, Insulation.

Introduction

The circumstances surrounding the evaluation of high voltage (HV) insulation system to decrease the danger and to prevent breakdown of the insulation of key units like transformers is a motivation to the utility Companies to use such evaluation techniques [5, 6]. An increase demand as well as bulk power dealings increase the rate of transformer ageing due to escalating rate of the operating stresses [6]. The failure of HV transformers are due to insulation breakdown caused by mechanical, thermal and electrical ageing [8]. It is therefore, important to have a well documented diagnostic method, so that potential insulation problems can be attended to during scheduled outage time.

The high voltage transformer 400 / 300 000 V transformer in the high voltage laboratory was manufactured in 1967 and it is necessary to evaluate the condition of the insulation to ensure a safe environment when experiments are done in the laboratory. The measurements done on the 22 kV voltage transformer forms the basis to prove the validity of the evaluation methods on a 300 kV transformer.

The methodology followed in this paper is made up of Phase Resolved Partial Discharge (PRPD) Measurements and Evaluation. PRPD evaluation is a method that displays the PD activity in a three- dimensional (3D) way to identify the phase relationship, the magnitude of the PD activity and finally the discharge rate and is well-suited for on-line measurements [2]. The measurements were done using an ICM*monitor* (from Power Diagnostix) which fully complies with the requirements of IEC 60270 method to measure partial discharges. PRPD patterns help to identify the behaviour of PD, its defect geometry and the intensity of the defect [9]. The experimental results from PRPD measurements using a Coupling Capacitor and the measurements using high frequency current transformers (HFCT's) are shown and compared.

PD diagnostic on transformers

PD measurement using coupling capacitor

The circuit arrangement shown in figure 1 is the conventional PD test circuit in accordance with IEC 60270 [4] consisting of HV power supply, the test object (Capacitance of VT to earth) Ck, the Coupling Capacitor Cc, the measuring impedance Zm, and the PD measuring device which consist of the ICM*monitor* from Power Diagnostix and personal computer with software to evaluate and save the data.
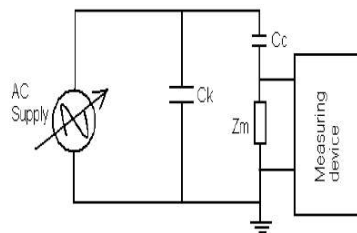
Figure1 (a): PD measuring circuit

Figure1 (b): A photo of Lab. Setup.

Figure 2(a and b) shows the results of the measurements with an applied voltage of 17.5 kV with the coupling capacitor as detection device. The system was calibrated using a calibration pulse magnitude of 5 pico Coulomb (pC).
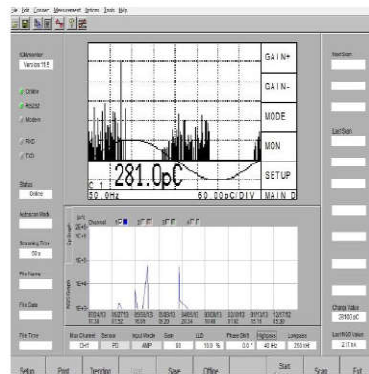
Figure2 (a): PD at 17.5 kV
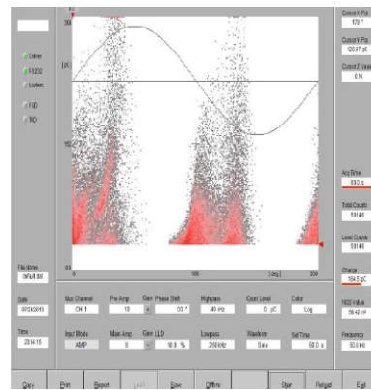
Figure2 (b): PRPD pattern at 17.5 kV

PD measurement using CT1 in earth lead.

CT1 is a high frequency current transformer with a window of 15 mm and is a fixed installation as the earth lead must be threaded through the window. The sensitivity of HFCT's is increased due to the ferrite material used as core material [1] and detects the PD signals in a wide frequency band [3]. CT1 has a -3dB bandwidth of 0.5-80 MHz and a -6dB bandwidth of 0.3-100 MHz.

Figure 3 shows the laboratory setup and figure 4 (a and b) the measurement results obtained with CT1.
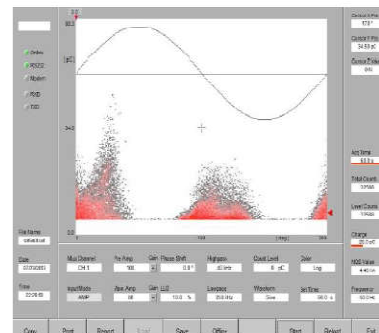
Figure3: Laboratory setup

Figure4 (a): PD at 17.5 kV

Figure4 (b): PRPD pattern at 17.5 kV
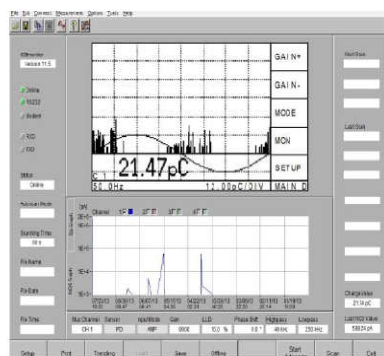
PD measurement using CT100 in earth lead

CT100 is a clamp – on high frequency current transformer with a window of 100 mm which is placed around the earth lead. CT100 can therefore be applied without any disconnection of earth leads or interruption of the supply.

It has a -3dB bandwidth of 2-25 MHz and a -6dB bandwidth of 1.2-40 MHz. Figure 5 shows the laboratory setup and Figure 6 (a and b) is the results obtained.
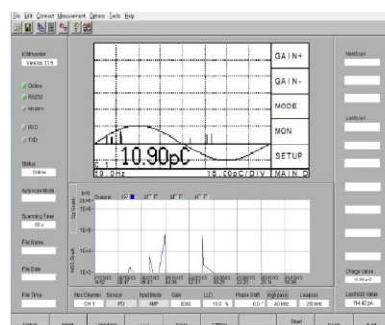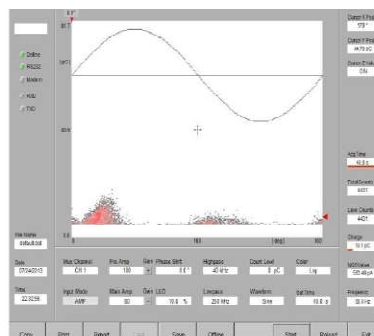
Figure5: Laboratory setup

Figure6 (a): PD at 17.5 kV

Figure6 (b): PRPD at 17.5 kV

Comparison of results and explanation

PD activities in the transformer are detected by the three different measurement systems. The PRPD results also show that the partial discharge occur during both positive and negative half – cycles and the discharge patterns are comparable.

From figure 2(b), 4(b) and 6(b), it is clear that, the patterns are as a result of internal void discharges in the voltage transformer [7].

Comparison of the results obtained, shows that the PD pulses measured with the coupling capacitor have greater magnitude than the pulses measured with the HFCTs. The pulses measured with CT1 also have greater magnitude compared to the results with CT100.

Both coupling capacitor and HFCTs sensors detected PD signals as shown in figure 2(a), 4(a) and 6(a). The HFCT's do not detect some PD pulses with some amount of energy as shown in figures 4(a) and 6(a). The differences in the measurement results can be attributed to the size of the air gap between the conductor and the CT core, the frequency bandwidth of the current transformers and the capacitance of the transformer winding which play a significant role in the measurement with the current transformers. This can occur when the frequency bandwidth of the PD pulses is low [3].

Conclusion

This paper presented two detection methods to evaluate the condition of a 22 kV voltage transformer. It was established by means of PRPD evaluation that an internal void discharges are present in the VT. From the results obtained from all the measurement systems, it is clear that HFCT sensors can be used to measure partial discharges in high voltage transformers. It is also shown that the coupling capacitor has a better sensitivity than HFCTs. However CT1 with a smaller window and different bandwidth is more sensitive than CT100 with the larger window.

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February 2008. Pp. 259 – 267.

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Annexure B: Conference Paper, 30-31 January 2014, Durban, South Africa

Partial Discharge Evaluation of a High Voltage Transformer

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Abstract: This paper describes the procedures followed to evaluate the condition of the insulation of a 11 kV Voltage transformer (VT) in the High Voltage Laboratory at Vaal University of Technology through measurement of partial discharges. This is the second part of the evaluation of the insulation of the 300 kV transformer in the high voltage laboratory. The method employed in this evaluation to detect the partial discharge signals, namely, the use of Capacitive Coupling by means of a Coupling Capacitor. The partial discharge evaluation methodology followed consists of measurement of the partial discharge magnitude and Phase Resolved Partial Discharge Measurements. The results from the measurement of partial discharge signal detection method are discussed.

Keywords: Partial Discharge, Voltage Transformers, Coupling Capacitor, Evaluation, Insulation.

1. INTRODUCTION

The circumstances surrounding the evaluation of high voltage (HV) insulation system to decrease the danger and to prevent breakdown of the insulation of key units like transformers is a motivation to the utility Companies to use such evaluation techniques [6, 7]. An increase demand as well as bulk power dealings increase the rate of transformer ageing due to escalating rate of the operating stresses [7]. The failure of HV transformers are due to insulation breakdown caused by mechanical, thermal and electrical ageing [9]. It is therefore, important to have a well documented diagnostic method, so that potential insulation problems can be attended to during scheduled outage time.

The high voltage transformer 400 / 300 000 V transformer in the high voltage laboratory was manufactured in 1967 and it is necessary to evaluate the condition of the insulation to ensure a safe environment when experiments are done in the laboratory. The measurements done on the 11 kV voltage transformer forms the basis to prove the validity of the evaluation methods on a 300 kV transformer.

The methodology followed in this paper is made up of Phase Resolved Partial Discharge (PRPD) Measurements and Evaluation. PRPD evaluation is a method that displays the PD activity in a three-dimensional (3D) way to identify the phase relationship, the magnitude of the PD activity and finally the discharge rate and is well-suited for on-line measurements [3]. Figure 1(a) and 1(b) shows the different between the traditional and the 3D PRPD patterns for the same defect.
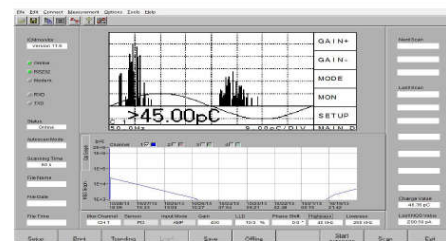
(a)
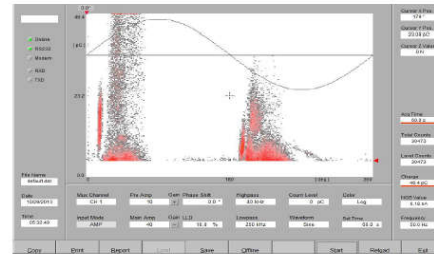
(b)

Figure 1: (a) Traditional PRPD pattern (b) 3D PRPD pattern

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The measurements were done using an ICM*monitor* (from Power Diagnostix) which fully complies with the requirements of IEC 60270 methods to measure partial discharges. PRPD patterns help to identify the behaviour of PD, its defect geometry and the intensity of the defect [10]. The experimental results from PRPD measurements using a Coupling Capacitor are discussed.

2. PD DIAGNOSTIC ON TRANSFORMERS

2.1 PD measurement using coupling capacitor

The circuit arrangement shown in Figure 2 consisting of HV power supply, the test object, the Coupling Capacitor Cc, the measuring impedance Zm, and the PD measuring device which consist of the ICM*monitor* from Power Diagnostix and personal computer with software to evaluate and save the data. The HV side of the voltage transformer were connected to the coupling capacitor and energized. The LV side and the insulation were grounded as an attempt to measure PD activity and also identify the type of PD. Acquired PD patterns were measured at different voltage levels.
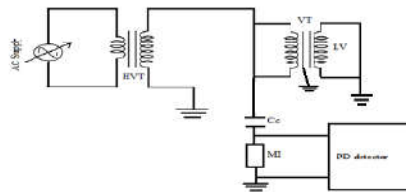
Figure 2: Partial discharge measuring circuit

Figure 3 shows the results of the measurements with different applied voltages with the coupling capacitor as detection device. The system was calibrated using a calibration pulse magnitude of 5 pico Coulomb (pC).
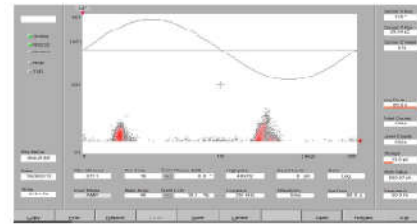
(a) 7.5 kV (13.6 pC)
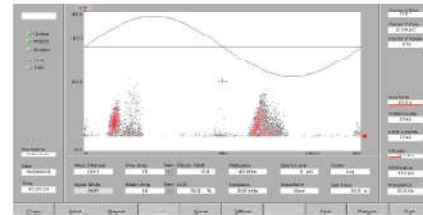
(b) 8 kV (18.7 pC)
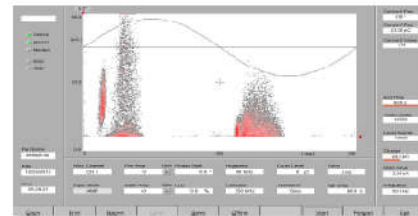
(c) 9 kV (24.2 pC)
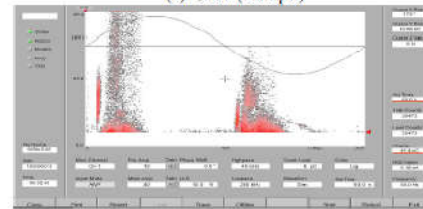
(d) 10 kV (46.4 pC)

Figure 3: PRPD pattern measured on an 11 kV VT

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3. MEASUREMENT WITH ONE SIDE OF HV CONNECTED TO CC AND ONE OF THE LV SIDE GROUNDED

Figure 4 shows the conventional PD test circuit in accordance with IEC 60270 [5] and 60073-3 [6]. Figure 5 shows the PRPD pattern obtained from the 11 kV voltage transformers. The acquired PD was measured at 7.5 kV and 10 kV, 15 kV and 16 kV. The knee-point voltage of the transformer was measured at 12 kV with the last two measurements when the transformer core was saturated.
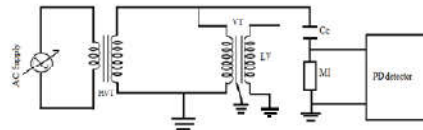
Figure 4: Partial discharge measuring circuit
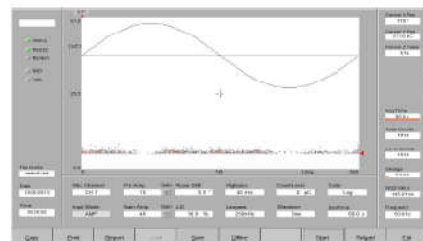
(a) 7.5 kV (5.4 pC)
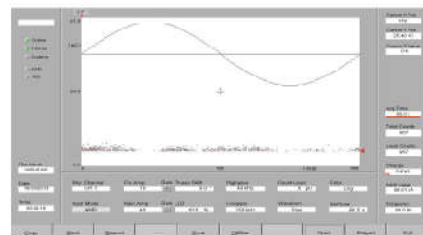
(b) 10 kV (5.2 pC)
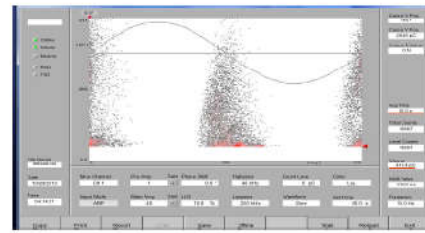
(c) 15 kV (410.4 pC)
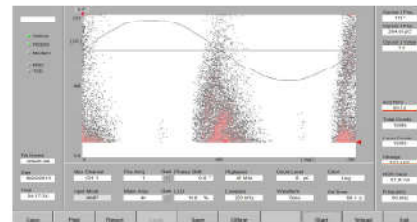
(d) 16 kV (531.3 pC)

Figure 5: PRPD pattern measured on an 11 kV VT

4. EXPLANATION OF RESULTS

Figure 3 shows PRPD patterns of cavity discharge in the insulation of the high voltage winding when the low voltage winding and core are grounded and HV side are connected to the coupling capacitor as shown in Figure 2. When the applied voltage is higher, the numbers of PDs per cycle, total charge per cycle and the maximum magnitude of the cavity discharge are higher. A partial discharge normally occurs in the cavity when the electric field in the cavity is higher than the inception field and there is an initial free electron to start an avalanche process. Since the process of having a free electron is random, the occurrence of a cavity discharge is also random [2].

When the applied voltage is increased, the maximum discharge magnitude is larger because the maximum electric field in the cavity is higher. At higher applied voltage, the electric field in the void increases faster towards the inception field. This results in more discharges in one applied voltage cycle. When the void is located in the middle of the material, the electric field on the surface

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of the void is symmetrical and the discharge patterns of cavity discharge at positive and negative cycles of the applied voltage will also be symmetrical [2]. The magnitudes of the discharges at the different applied voltages are shown in Figure 3.

Figure 5 shows the discharge patterns when the transformer is excited from the high voltage winding as shown in Figure 4. There were no discharges recorded below the knee point voltage of 12 kV as shown in Figure 5(a) and 5(b). Partial discharge activity was only recorded above the knee point voltage as shown in Figure 5(c) and 5(d). The discharges occur at the zero crossings of the applied voltage. One of the possible reasons for the discharges only occurring above the knee-point voltage can be the distortion of the induced voltage when the core is saturated. The peak of the distorted induced voltage will increase as the core goes deeper into saturation. The PRPD pattern seen also indicates that the discharges are not due to a cavity in the insulation but can rather be attributed to surface discharges [2].

The reason why the discharges occurring when the connection as in Figure 2 did not appear during the second test (Figure 4) can be that the defect is in the high voltage insulation at the end of the winding connected to earth during the second test. The defects were therefore not stressed enough for discharges to occur. This postulate was not tested and will be investigated during further tests.

5. CONCLUSION

This paper presented two methods to evaluate the condition of a 11 kV voltage transformer using the electrical method of partial discharge detection [5]. Two types of discharges have been evaluated in this paper using PRPD technique. From the results obtained both connection systems resulted in discharge activity not detected by the other system. When using the connection proposed in the standards [5] defects appearing in the section of the high voltage winding insulation connected to earth will possibly not be detected while the magnitude of the applied voltage (above the knee-point) can cause the core to saturate resulting in discharge activity.

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Annexure C: Conference Paper presented on, 8-11 September 2014, Poznan, Poland.

Partial Discharge Pattern Characterization of Different Defects Using 3D Phase Resolved Technique

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Abstract: This paper describes the procedures to characterize defects in the insulation of an 11 kV Voltage Transformer (VT) by evaluation of the 3D phase-resolved partial discharge patterns. The 3D Phase-Resolved Technique provide a method to identify defects where partial discharges occur by means of the unique character of the phase relationship - the magnitude of the partial discharge activity and the discharge rate of the defects.

Partial discharges occurring in solid insulation can be characterized by means of the shape of the defect, viz spherical, ellipse, cracks in the insulation and delamination on interfaces with electrodes. The location of the defects in relation with the distance from the high voltage electrode or earth electrode also connoted in the pattern displayed. The last variable that determines the final pattern is the number of discharges occurring over a specific time, or which can be given as the rate of discharge in the specific defect.

The methodology consists of measurement of the partial discharges in solid samples insulation; having known the defects of different shapes and at the specific locations in the insulation. The defects were manufactured into the samples at pre-determined locations and having different shapes and sizes. The specific defect patterns obtained from the samples were used to identify the type of defects and locations in the insulation of the voltage transformer. The paper further describe the different results obtained based on the method of excitation of the voltage transformer.

I. INTRODUCTION

The conditions surrounding the evaluation of High Voltage (HV) insulation system to decrease the danger and to prevent breakdown of the insulation of key units like transformers are motivations to the utility Companies to use such evaluation techniques [1,2]. An increase demand as well as bulk power dealing increases the rate of transformer ageing due to the effect of escalating rate of the operating stresses [1]. The failure of HV transformers is because of insulation breakdown caused by mechanical, thermal and electrical ageing [3].

However, the methodology in this paper is made up of Phase Resolved Partial Discharge (PRPD) measurements and evaluation. PRPD evaluation is the method that displays the Partial Discharge (PD) activity in a three-dimensional (3D) way to identifying the phase relationship, the magnitude of the PD activity and the discharge rate. This complied with on-line measurements [4]. The PRPD patterns provide detailed information to analyze the condition of the insulation to prevent failures in high voltage systems. 3D partial discharge mappings are used to characterize the partial discharge concentration in the specific areas of the equipment [5]. Each single coloured dot represents the number of PD occurred with given amplitude and phase [6].

Additionally, in this paper, spherical cavity is considered since the insulation of the voltage transformer (VT) is made of epoxy resin insulator which will be made easier to correlate the patterns of the artificial defects with the patterns found in the VT.

II. ARTIFICIAL DEFECTS

The sample used in the measurement consist of an 11 kV XLPE insulation and an artificial cavity within the insulation. Figure1 shows the three test objects that were used in the experiment. The cavity was artificially created by drilling a hole in the insulation layer of the samples. Figure1 (a) consist of the cavity within the XLPE insulation covered with heat shrink insulation. The cavity diameter was 5mm and the thickness of the insulation was 4.6mm. Figure1 (b) consist of the XLPE insulation covered with a layer of heat shrink insulation. The cavity with the diameter of 5mm was created within the 3.2mm thick of the heat shrink. The void was covered with another layer of heat shrink. Figure1(c) also consist of the cavity of 5mm diameter within the XLPE insulation of 4.6mm thick. The cavity was covered with two layers of heat shrinks.

(a)
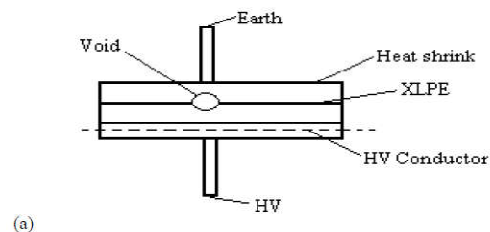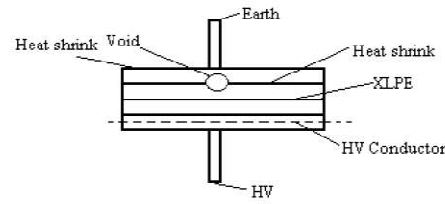
(b)
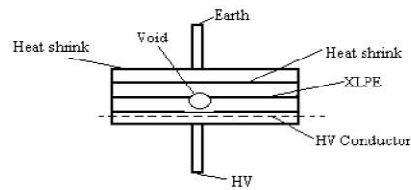
(c)

Figure 1. Artificial void in solid insulation: (a) void in the middle of the insulation, (b) the void is closer to the earth, (c) the void is closer to high voltage

The circuit arrangement shown in figure2 is the conventional PD test circuit in accordance with IEC 60270 [7] consisting of 50 Hz ac power supply, the test sample, the Coupling Capacitor (Cc), the measuring impedance (Zm), and the PD measuring device which consist of the ICM*monitor* from Power Diagnostix and personal computer with software to evaluate and save the data. Figure3 shows the results of the measurements with an applied voltage of 2.5 kV.
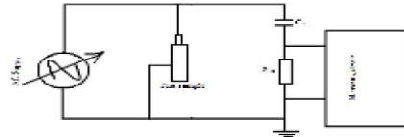
Figure 2. PD measuring circuit

Figure3 shows phase resolved patterns for the partial discharge activities of the test samples in figure1. An increasing voltage of 0 – 2.5 kV is applied to measure the partial discharge within the solid insulation. Generally, it is seen that, partial discharge pulse appears around 330 – 90 degree phase angle in positive half cycle and 150 – 270 degree phase angle in negative half cycle of the 2.5 kV applied voltage. To observed PD activity within an enclosed cavity between the solid insulation and copper, the material operates as anode and

cathode in the positive and negative half cycles. The cathode material provides free electrons to initiate partial discharges which then create plasma on the surface of the insulation. Plasma accelerates partial discharge activity as it is a very good source of free electrons. As a result, there is a likelihood of partial discharge activity taking place when the insulation material is acting as a cathode [9].
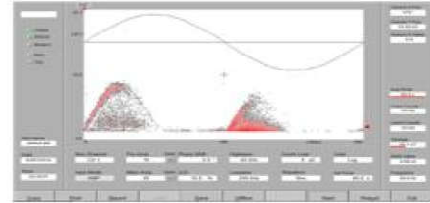
(a)
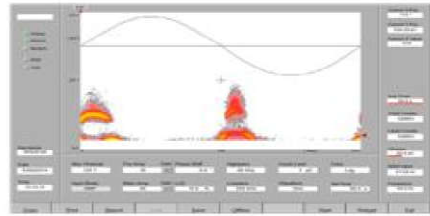
(b)

(c)
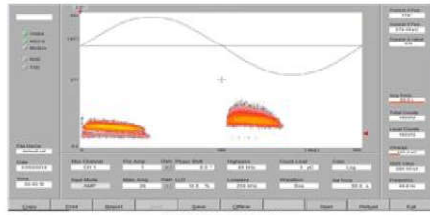
Figure 3. PRPD patterns of test samples at 2.5 kV at: (a) 28.4 pC, (b) 22 pC, (c) 165.2 pC

For both positive and negative half cycles, the XLPE insulation itself remains the cathode, therefore there will be a balance of activity within the cavity making the partial discharge patterns obtained symmetrical between positive and negative half cycles as shown in figure3 (a). When the void is located in the middle of the insulation, the electric field magnitude in the void is higher than the surround cable

insulation due to lower permittivity in the void leading to higher electric field [10].

In the positive half cycle the insulation acts as a cathode and the copper acts as an anode. More electrons are supplied by the insulation, hence greater number of partial discharges in the positive half cycle as shown in figure3 (b). Figure3 (b) indicates that the cavity is located closer to the earthed electrode.

In the negative half cycle, the insulation material acts as a cathode across the cavity. The initial electrons to start partial discharges are released by the insulation hence larger number of partial discharges occurring during the negative half cycle as shown in figure3 (c). This confirmed that the cavity is closer to the high voltage electrode.

III. PARTIAL DISCHARGE PATTERNS IN THE VOLTAGE TRANSFORMER

A. PD measurement with both sides of low voltage connected to ground

The high voltage side of the voltage transformer were connected to the coupling capacitor and energized. The low voltage side and the insulation were grounded as an attempt to measure PD activity and also identify the type of PD. Acquired PD patterns were measured at different voltage levels. Figure4 shows the measuring circuit.
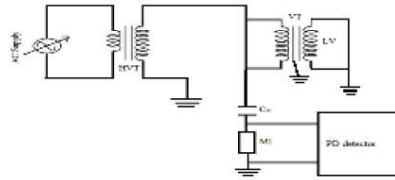
Figure 4. Partial discharge measuring circuit.

Figure6 shows the results of the measurements with different applied voltages with coupling capacitor as detection device. The system was calibrated using a calibration pulse magnitude of 5 pico Coulomb (pC).

B. Measurement with one side of HV connected to cc and one of the LV side grounded

Figure6 shows the conventional PD test circuit in accordance with IEC 60270 [7] and 60073-3 [8]. Figure7 shows the PRPD pattern obtained from the 11 kV voltage transformers. The acquired PD was measured at 10 kV and 15 kV. The knee-point voltage of the transformer was measured at 12 kV with the last measurement when the transformer core was saturated.
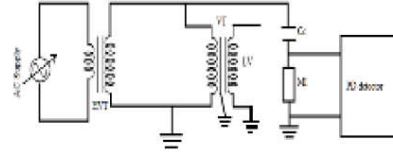
Figure 5. Partial discharge measuring circuit
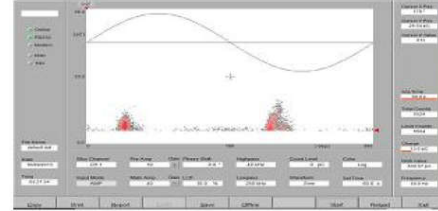
(a)
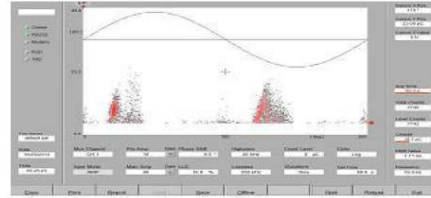
(b)

Figure 6. PRPD pattern measured on an 11 kV VT: (a) 7.5 kV at 13.6 pC, (b) 8 kV at 18.7 pC

Referring to Figure6, the number of partial discharges occurred in the negative half cycle is more than the positive half cycle. This is because more electrons are readily available from the electrode under negative half cycle, resulting in more electron avalanches easier to be developed. A partial discharge normally occurs in the cavity when the electric field in the cavity is higher than the inception field and there is an initial free electron to start an avalanche process [10]. Thus the phase resolved patterns of void discharge at positive and negative half cycles of the applied voltage not symmetrical.
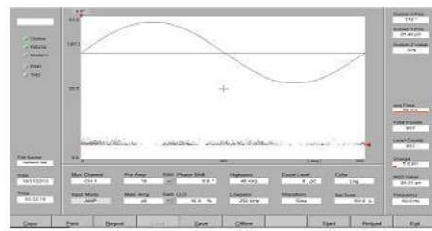
(a)
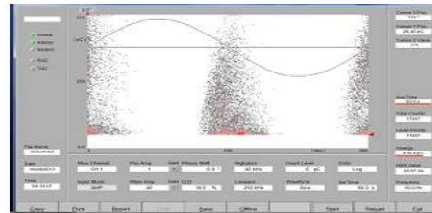
(b)

Figure 7. PRPD pattern measured on an 11 kV VT: (a) 10 kV at 5.2 pC, (b) 15 kV at 410.4 pC

It was observed from Figure7 that, no partial discharge was recorded with the applied voltage of $0 - 10$ kV which is below the knee point of 12 kV of the voltage transformer as shown in Figure7 (a). This is because the field intensity within the defect not exceeds beyond the breakdown strength of the gas in defect below the applied voltage of 10 kV. Further increases of applied voltage above the knee point of 15 kV results in partial discharges with higher amplitude as shown in Figure7 (b). The discharges occur at the zero crossings of the applied voltage. One of the possible reasons for the discharges only occurring above the knee-point voltage can be the distortion of the induced voltage when the core is saturated. The peak of the distorted induced voltage will increase as the core goes deeper into saturation [11]. The PRPD pattern seen also indicates that the discharges are not due to a cavity in the insulation but can rather be attributed to surface discharges [10].

The reason why the discharges occurring when the connection as in Figure4 did not appear during the second test (Figure 6) can be that the defect is in the high voltage insulation at the end of the winding connected to earth during the second test. The defects were therefore not stressed enough for discharges to occur. This postulate was not tested and will be investigated during further tests.

IV. CONCLUSION

3D phase resolved technique has been employed to characterize the defects in solid insulation materials and an 11 kV voltage transformer using the electrical method of partial discharge detection [7]. When using the connection proposed in the standards [7] defects appearing in the section of the high voltage winding insulation connected to earth will possibly not be detected while the magnitude of the applied voltage (above the knee-point) can cause the core to saturate resulting in discharge activity in the VT.

From the results obtained, it was established that the patterns of the artificial defects compare to the patterns obtained from the VT does not correlate.

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Annexure D: Turnitin originality report

Turnitin Originality Report

PROJECT1   by Isaac Kyere

From PROJECT1 (Class A)

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- ID: 440978267
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Illias, Hazlee, Teo Soon Yuan, Ab Halim Abu Bakar, Hazlie Mokhlis, George Chen, and Paul L. Lewin. "Partial discharge patterns in high voltage insulation", 2012 IEEE International Conference on Power and Energy (PECon), 2012.

paper text:

PARTIAL DISCHARGE EVALUATION ON HIGH VOLTAGE TRANSFORMER Isaac Kwabena Kyere 207001863 Dissertation submitted in the fulfilment of the requirements for the Magister Technologiae: Engineering: Electrical Department: Power Engineering Faculty of Engineering and Technology Vaal University of Technology Vanderbijlpark Supervisor: Prof. J.J Walker Co-Supervisor: Prof D.V Nicolae Co-Supervisor: Mr. B.J Le Roux Date: May 2014 DECLARATION I, Isaac Kwabena Kyere declare that this research is my own unaided work, except where specific acknowledgement is made by name, in the form of a reference. It is being submitted for the requirements for the Magister Technologiae: Engineering: Electrical to the Department: Power Engineering at the Vaal University of Technology, Vanderbijlpark. It has not been submitted before for any assessment to any educational institution. .... Isaac Kwabena Kyere Date: .... ii EDITING LETTER Ms Linda Scott English language editing SATI membership number: 1002595 Tel: 083 654 4156 E-mail: lindascott1984@gmail.com 21 July 2014 To whom it may concern This is to confirm that I, the undersigned, have language edited the thesis of i.K. Kyere for the Magister Technologiae: Engineering: Electrical degree thesis entitled: Partial discharge evaluation on high voltage transformer. The responsibility of implementing the recommended language changes rests with the author of the thesis. Yours truly, Linda Scott ii ACKNOWLEDGMENTS It is fitting to acknowledge my supervisor and moral mentor, Professor Jerry J. Walker, for all the efforts he has put into my academic development. I thank him

Annexure E: NRF Nexus title search report

NRF NEXUS SEARCH RESULTS

TO WHOM IT MAY CONCERN

This letter serves to inform that a literature search has been performed on behalf of

Mr.Kyere Isaac K. on the topic:

Partial Discharge Evaluation on High Voltage Transformer

Currently there are no records retrieved on the above research topic on NRF NEXUS DATABASE.

The search was conducted by MlulekiSiguntu Subject Information Specialist: Electrical Engineering Gold-Fields Academic Information Service on the 5th May 2011.

I thank you

Signed………………………………………………………

Mr MlulekiSiguntu
 Information Specialist
Engineering Faculty
Vaal University of Technology
Tel: (016) 950 9286
Email: mluleki@vut.ac.za

VUT Libraries - your information partner of Choice!

Annexure F: Partial discharge measurement using 1000 pF coupling capacitor (C1).
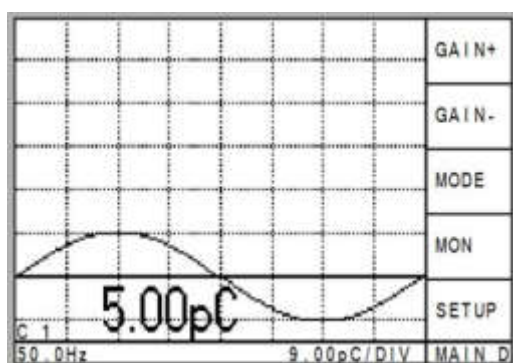
(a) 5,00 pC at 10 kV   (b) 6,67 pC at 20 kV
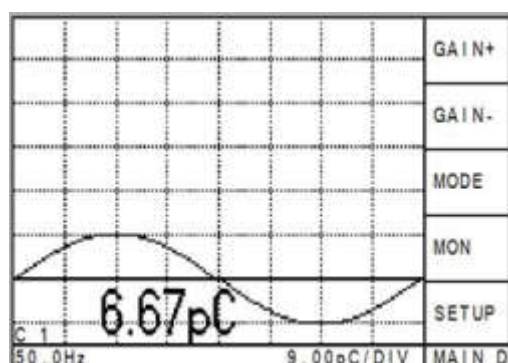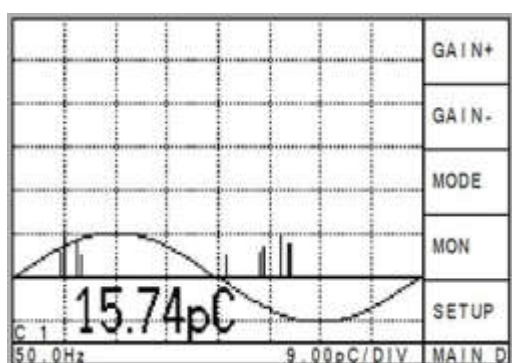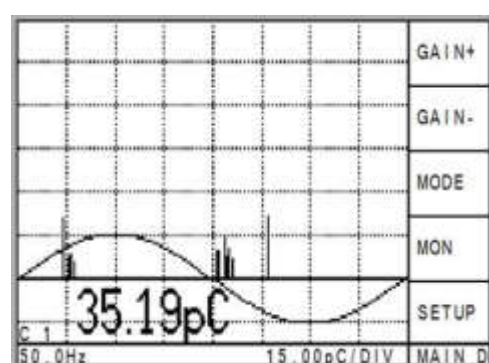
(c) 15,74 pC at 30 kV   (d) 35,19 pC at 40 kV
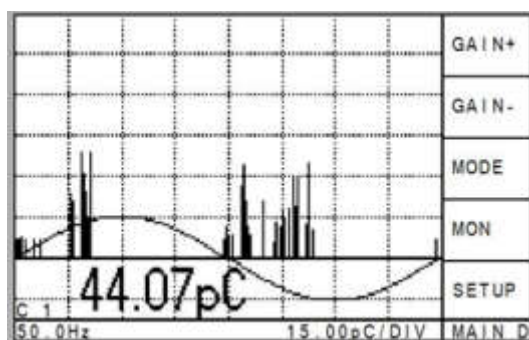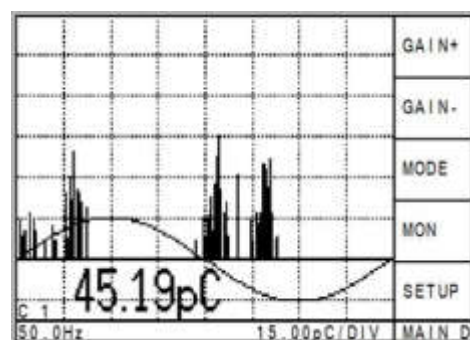
(e) 44,07 pC at 50 kV   (f) 45,19 pC at 60 kV

Typical Φ – n patterns for a 300 kV transformer .
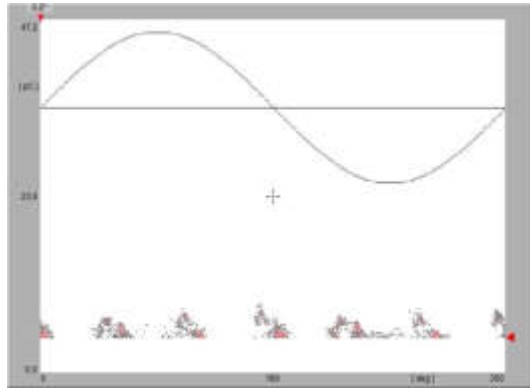
(a) 5,00 pC at 10 kV
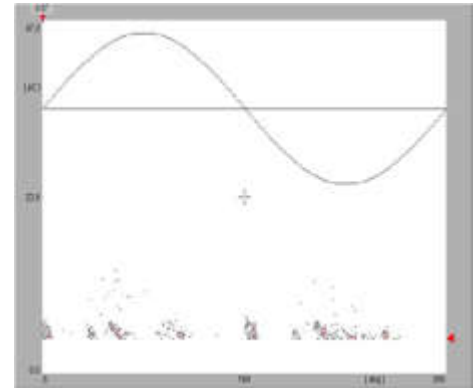
(b) 6,67 pC at 20 kV
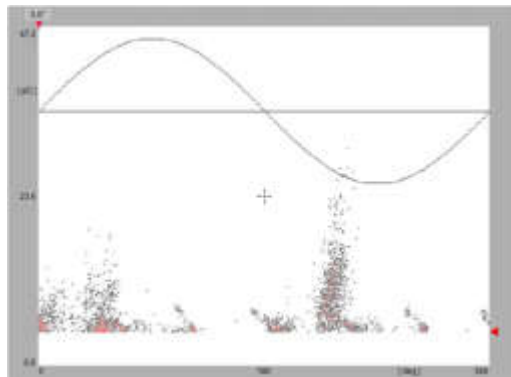
(c) 15,74 pC at 30 kV
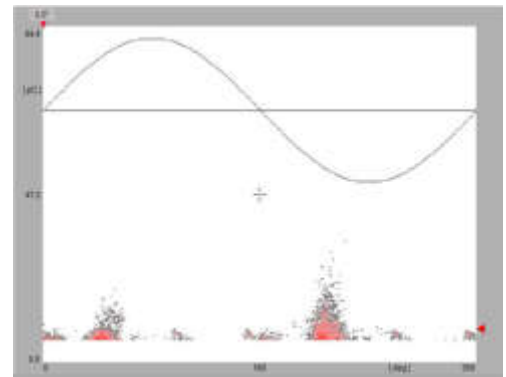
(d) 35,19 pC at 40 kV
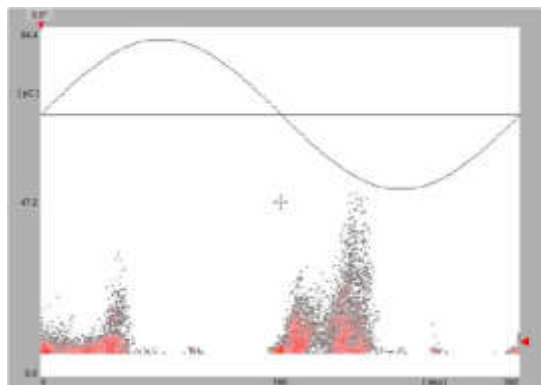
(e) 44,07 pC at 50 kV
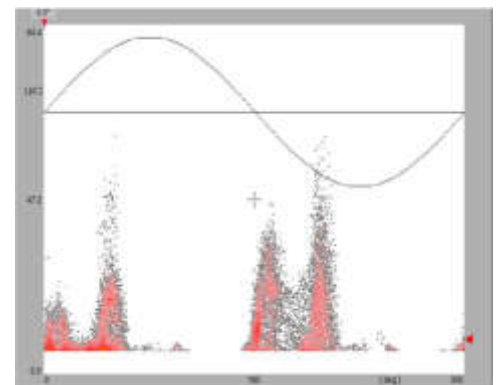
(f) 45,19 pC at 60 kV

Typical phase resolved PD pattern for 300 kV HV transformer

Annexure G: Partial discharge measurement using 1000 pF (C1) coupling capacitor with different setup.
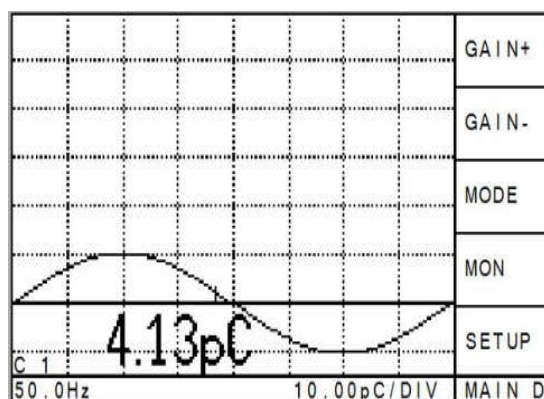
(a) 4,13 pC at 10 kV
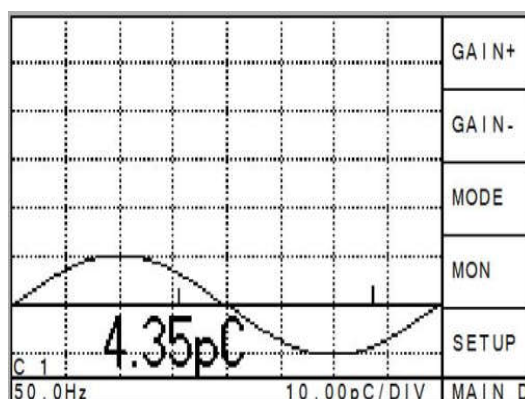
(b) 4,35 pC at 20 kV
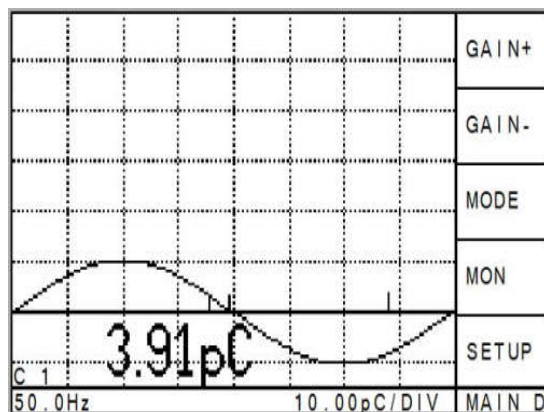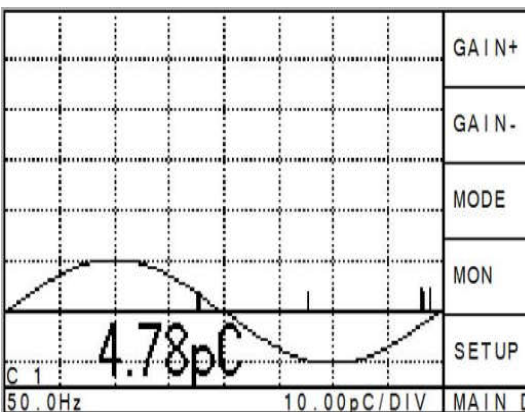
(c) 3,91pC at 30 kV
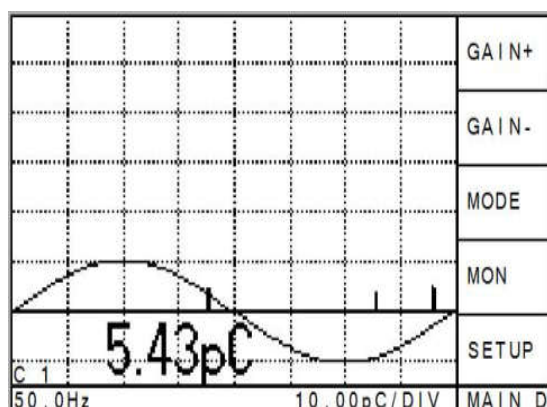
(d) 4,78 pC at 40 kV
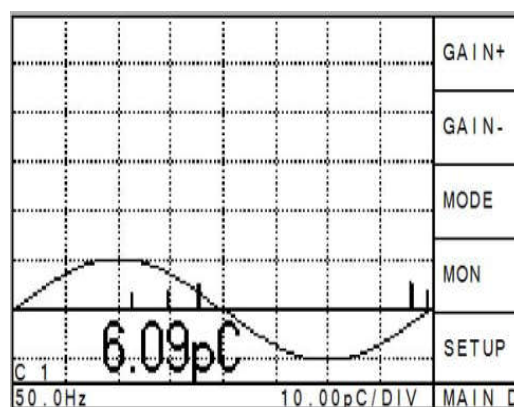
(e) 5,43 pC at 50 kV

(f) 6,09 pC at 60 kV

Partial discharge pulses recorded from the measurement on a 300 kV transformer.
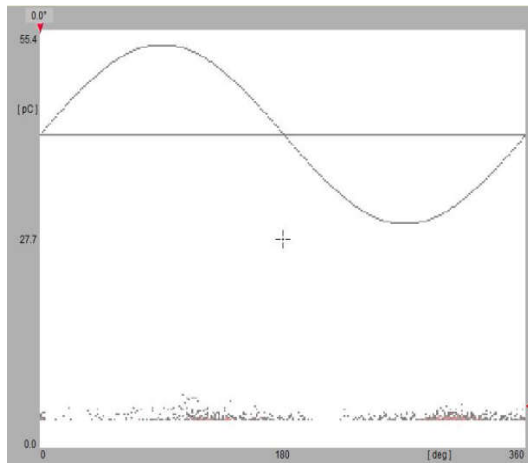
(a) 4,13 pC at 10 kV   (b) 4,35 pC at 20 kV
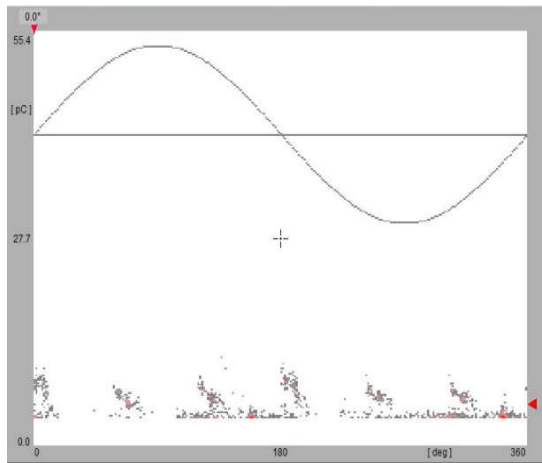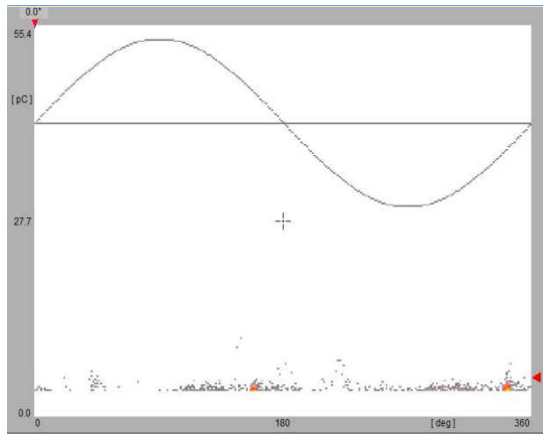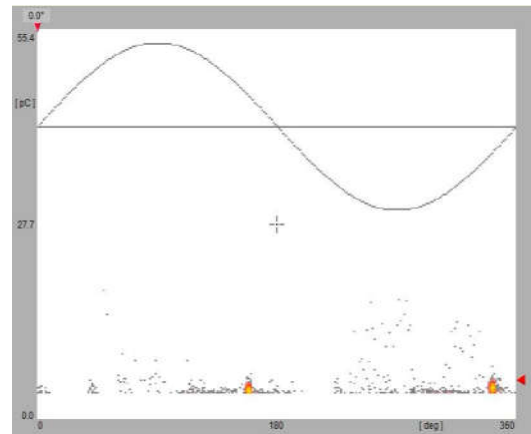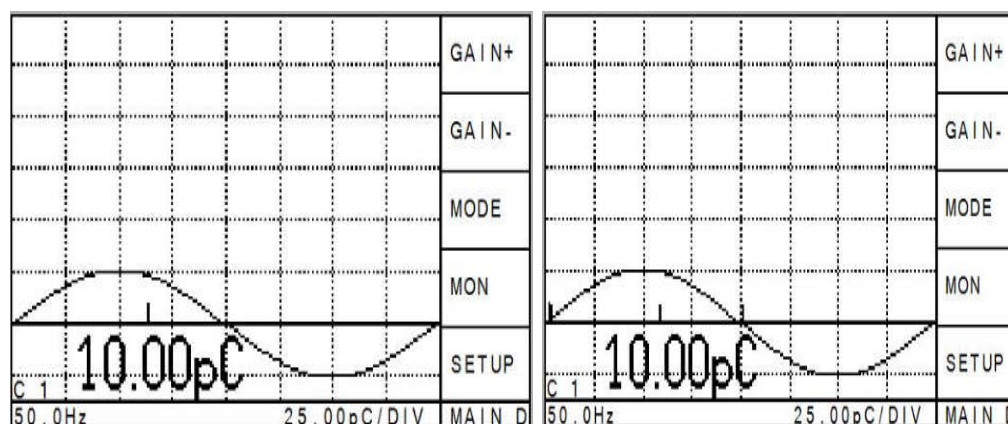
(c) 3,91pC at 30 kV   (d) 4,78 pC at 40 kV
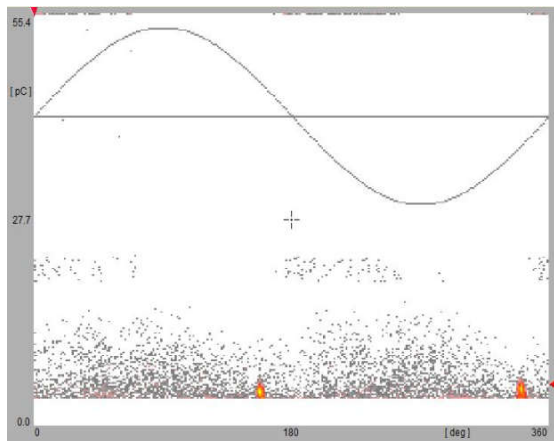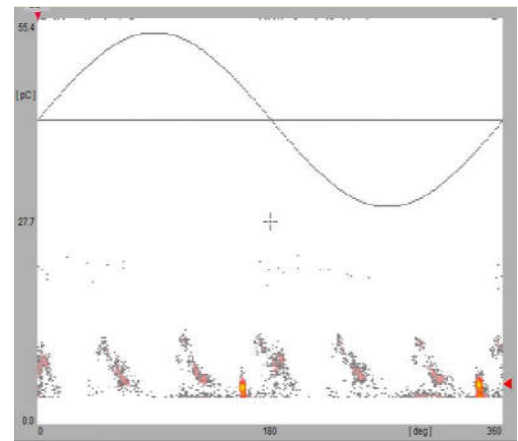
(e) 5,43 pC at 50 kV   (f) 6,09 pC at 60 kV

PRPD pattern measured on a 300 kV transformer.

Annexure H: **Partial discharge measurement using 1000 pF (C2) coupling capacitor.**
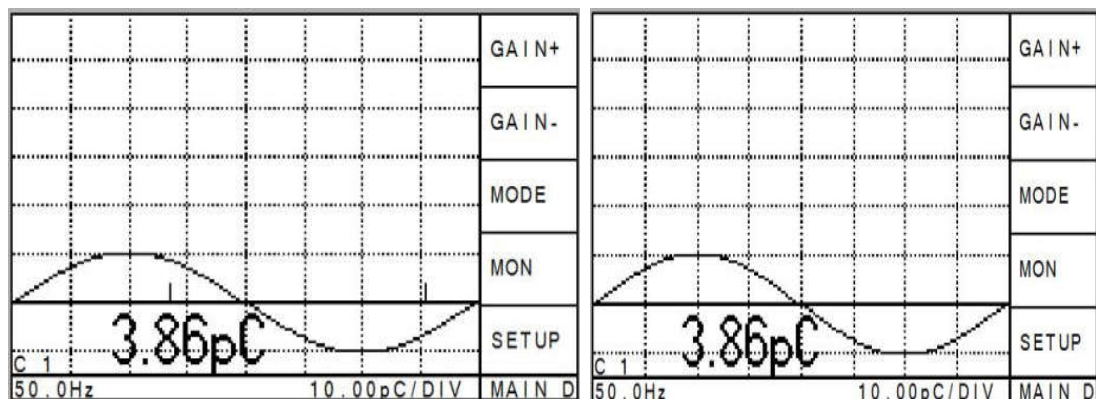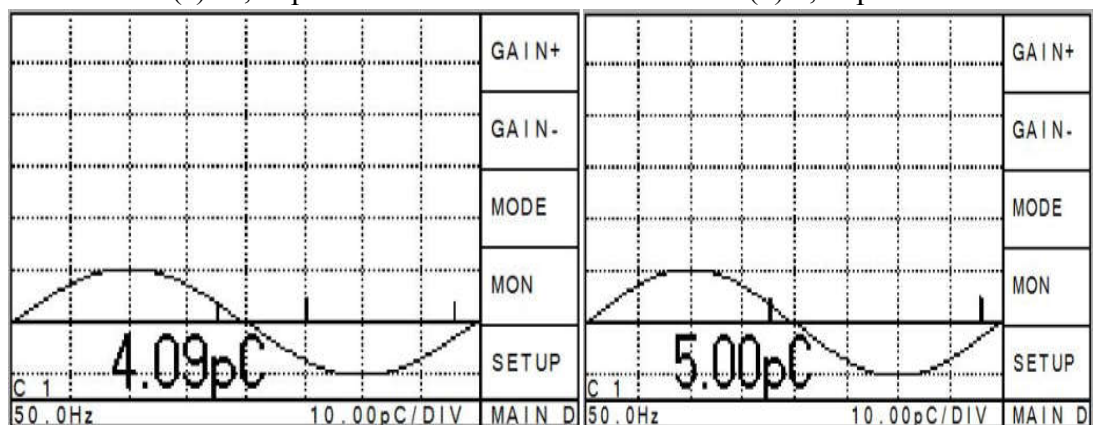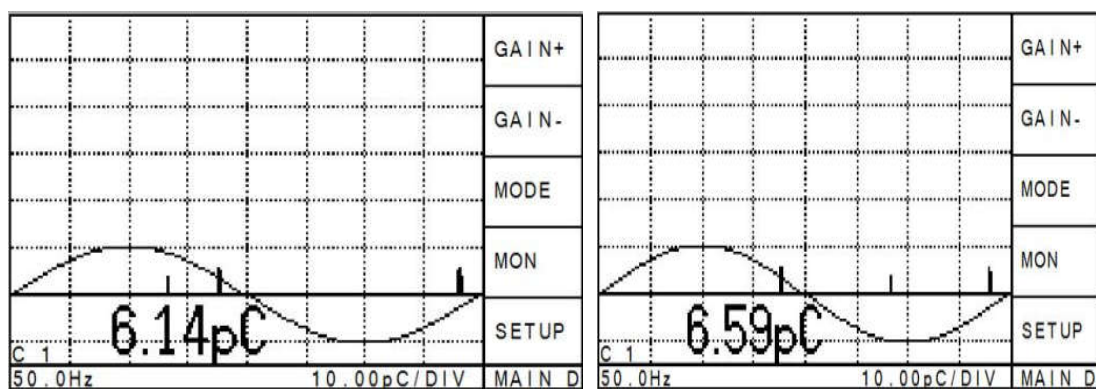
| (a) 3,86 pC at 10 kV | (b) 3,86 pC at 20 kV |

| (c) 4,09 pC at 30 kV | (d) 5,00 pC at 40 kV |

| (e) 6,14 pC at 50 kV | (f) 6,59 pC at 60 kV |

Partial discharge pulses recorded from the measurement on a 300 kV transformer.
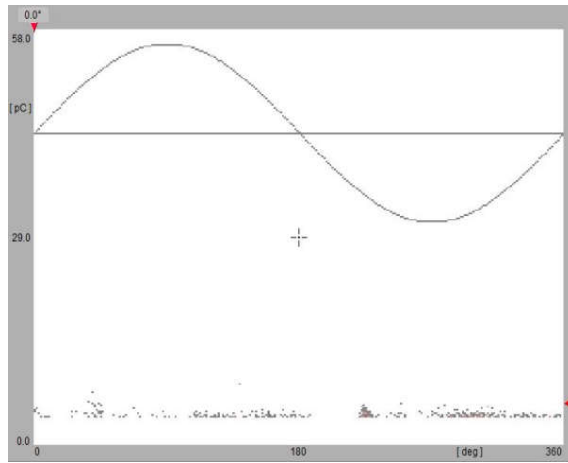
(a) 3,86 pC at10 kV
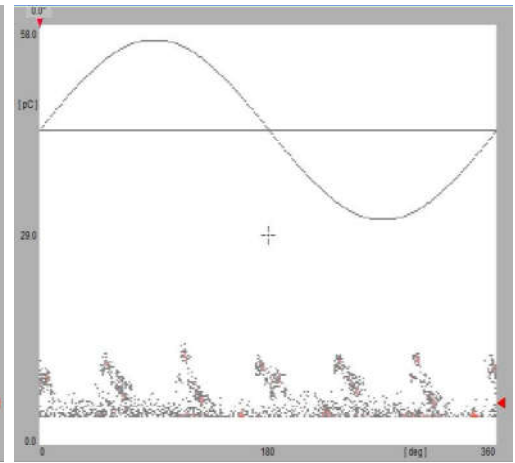
(b) 3,86 pC at 20 kV
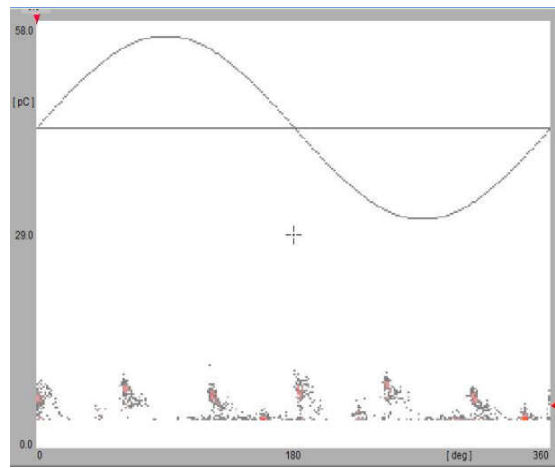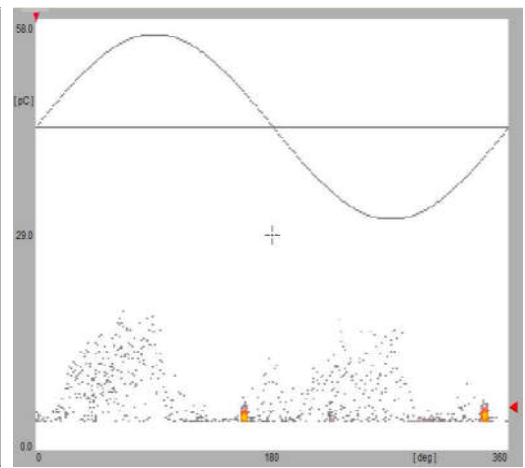
(c) 4,09 pC at 30 kV
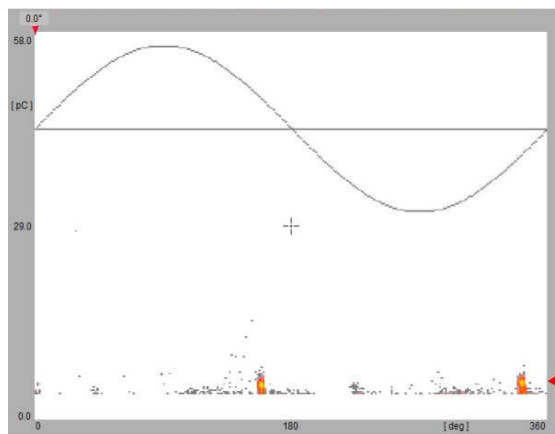
(d) 5,00 pC at 40 kV

(e) 6,14 pC at 50 kV
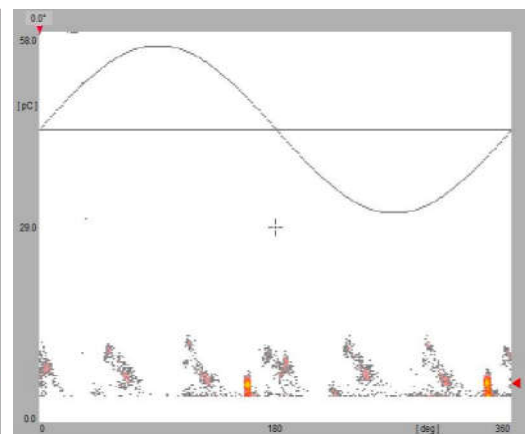
(f) 6,59 pC at 60 kV

PRPD pattern measured on a 300 kV transformer.

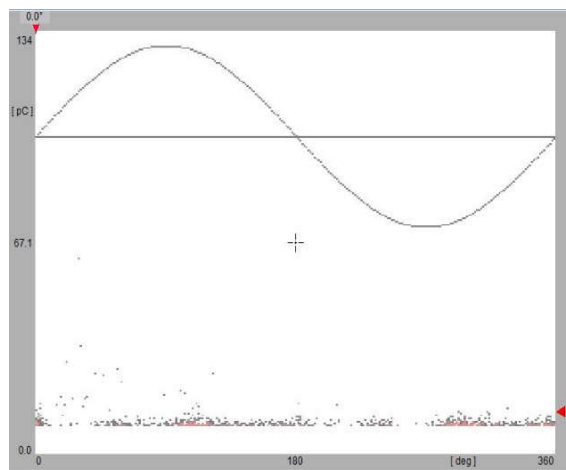**Annexure I**: **Partial discharge measurement using 500 pF coupling capacitor (C1+C2) with different setup.**
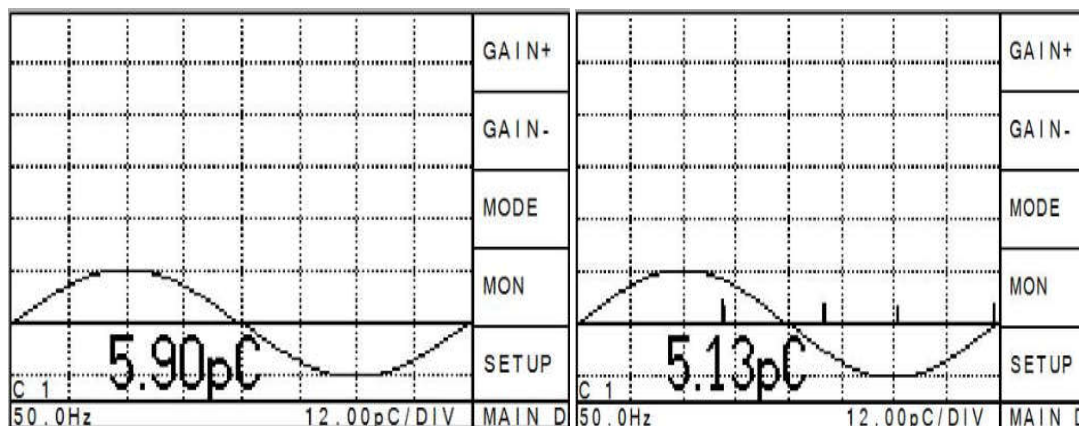
(a) 5,90 pC at 10 kV

(b) 5,13 pC at 20 kV
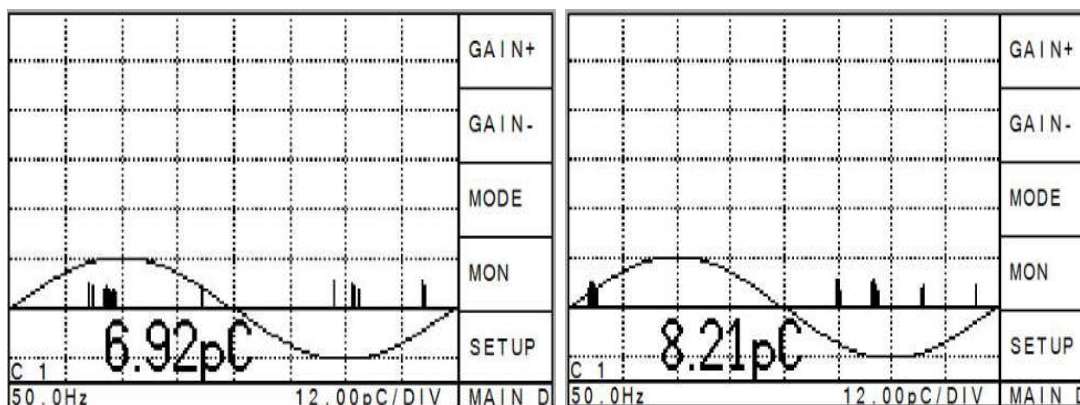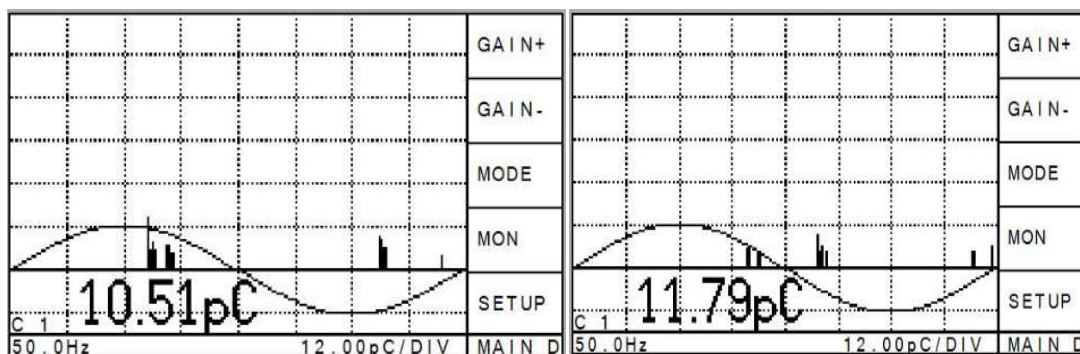
(c) 6,92 pC at 30 kV

(d) 8,21 pC at 40 kV

(e) 10,51 pC at 50 kV
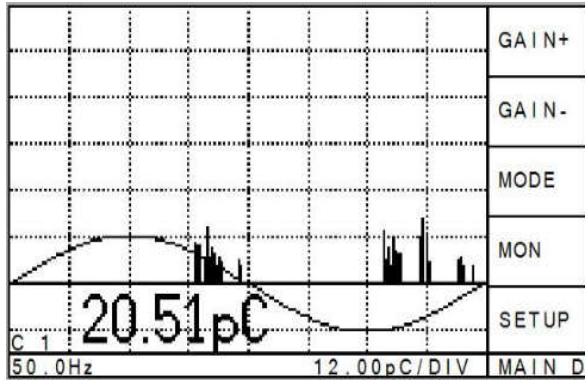
(f) 11,79 pC at 60 kV
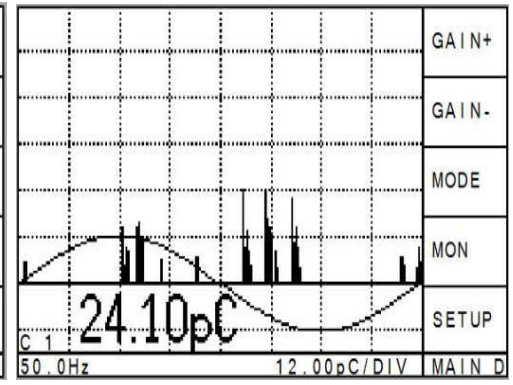
(g) 20,51 pC at 150 kV
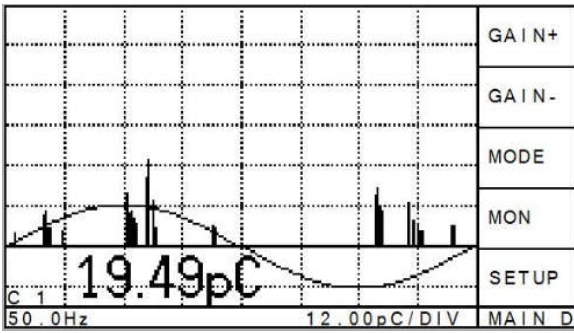
(h) 24,10 pC at 160 kV
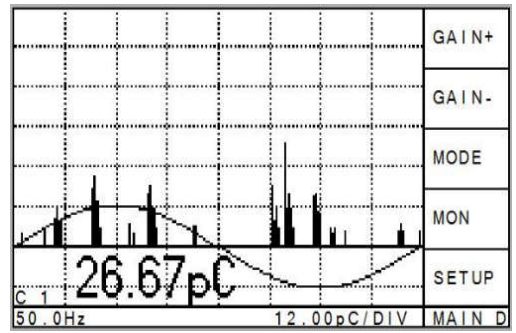
(i) 19,49 pC at 170 kV

(j) 26,67 pC at 180 kV

PD pulses recorded from the measurement on a 300 kV transformer.
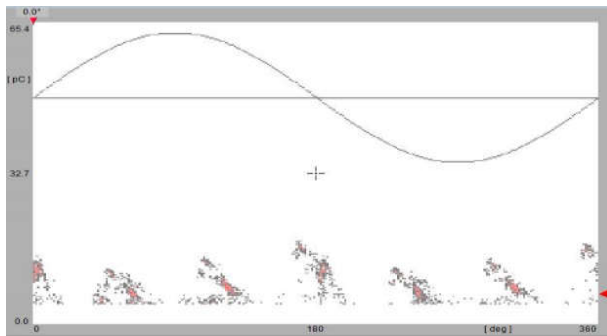
(a) 5,90 pC at 10 kV
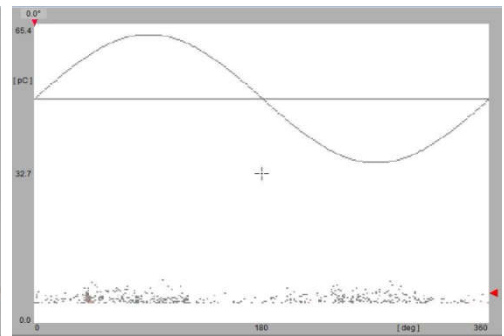
(b) 5,13 pC at 20 kV
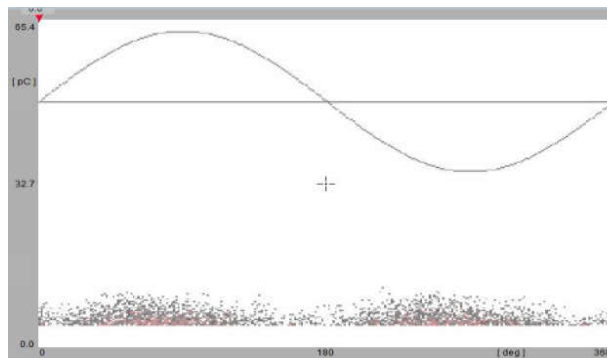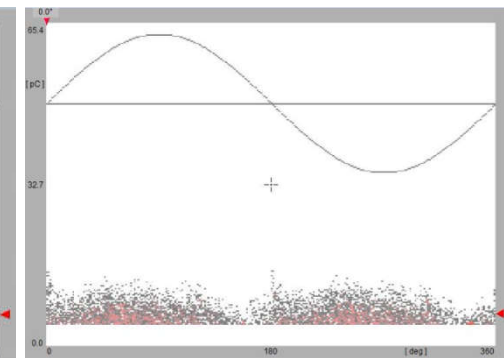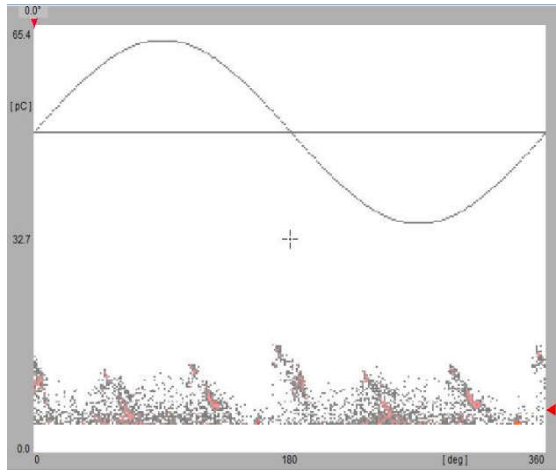
(c) 6,92 pC at 30 kV

(d) 8,21 pC at 40 kV
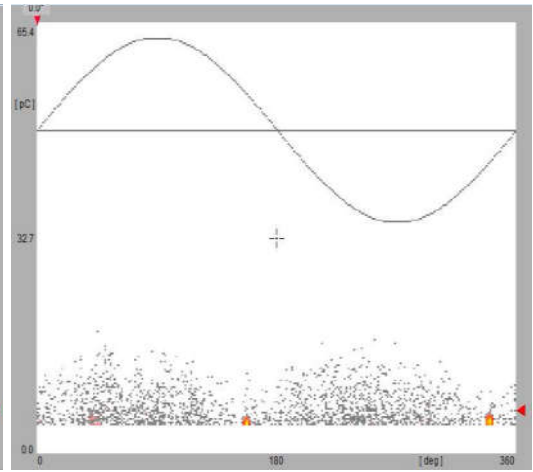
(e) 10,51 pC at 50 kV

(f) 11,79 pC at 60 kV
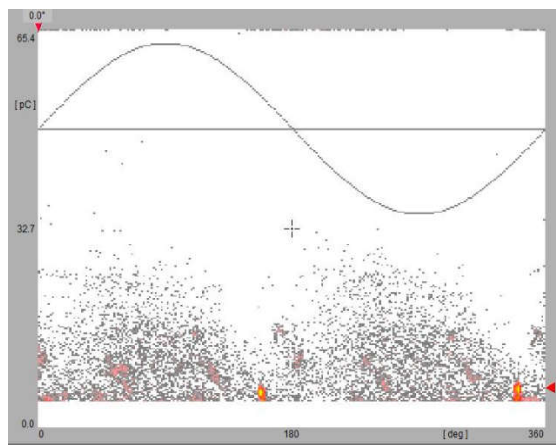
(g) 20,51 pC at150 kV
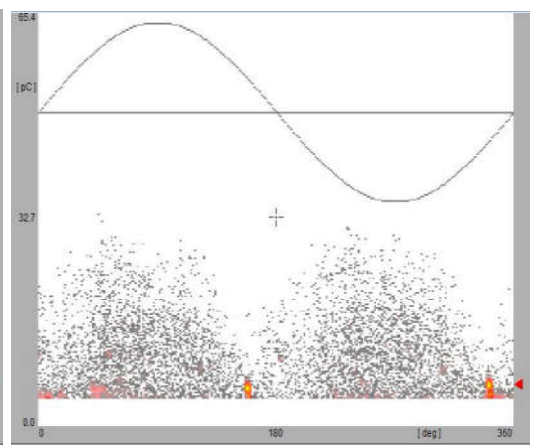
(h) 24,10 pC at 160 kV
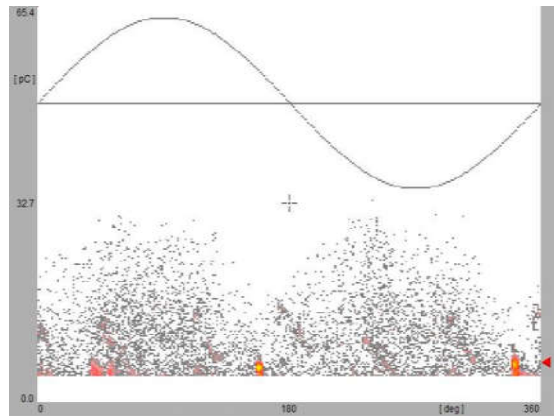
(i) 19,49 pC at170 kV
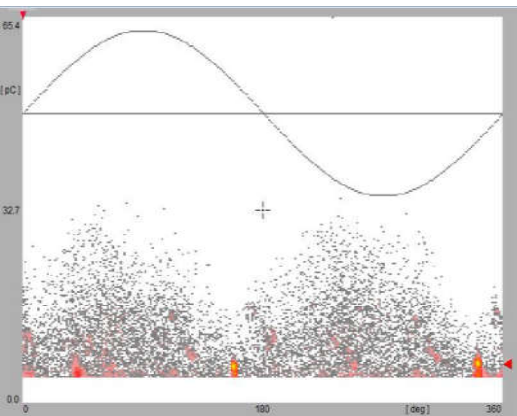
(j) 26,67 pC at 180 kV

PRPD pattern measured on a 300 kV transformer

Annexure J: **Partial discharge measurement using CT1**

(a) 10,00 pC at 50 kV

(b) 10,00 pC at 100 kV
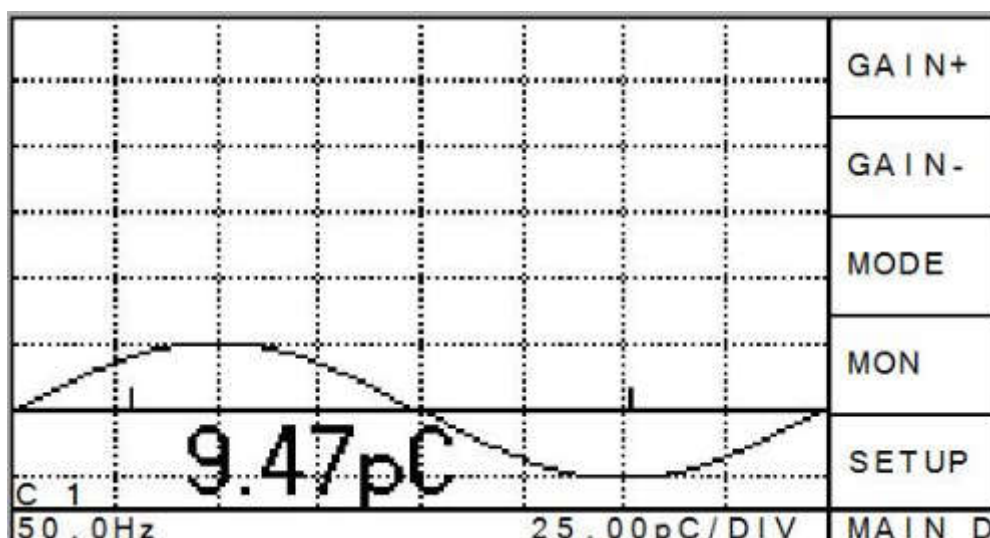
(c) 9,47 pC at 150 kV

Partial discharge pulses recorded from a 300 kV transformer.

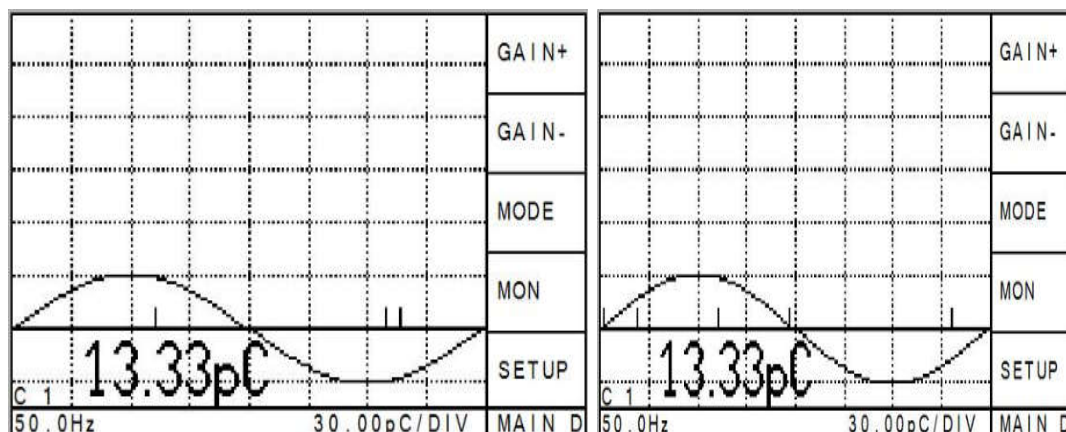(a) 10,00 pC at 50 kV
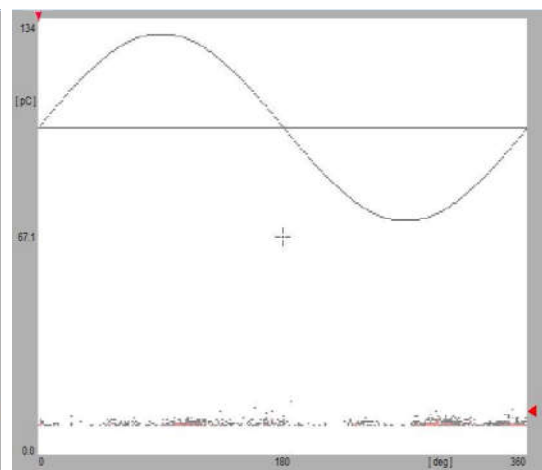
(b) 10,00 pC at 100 kV
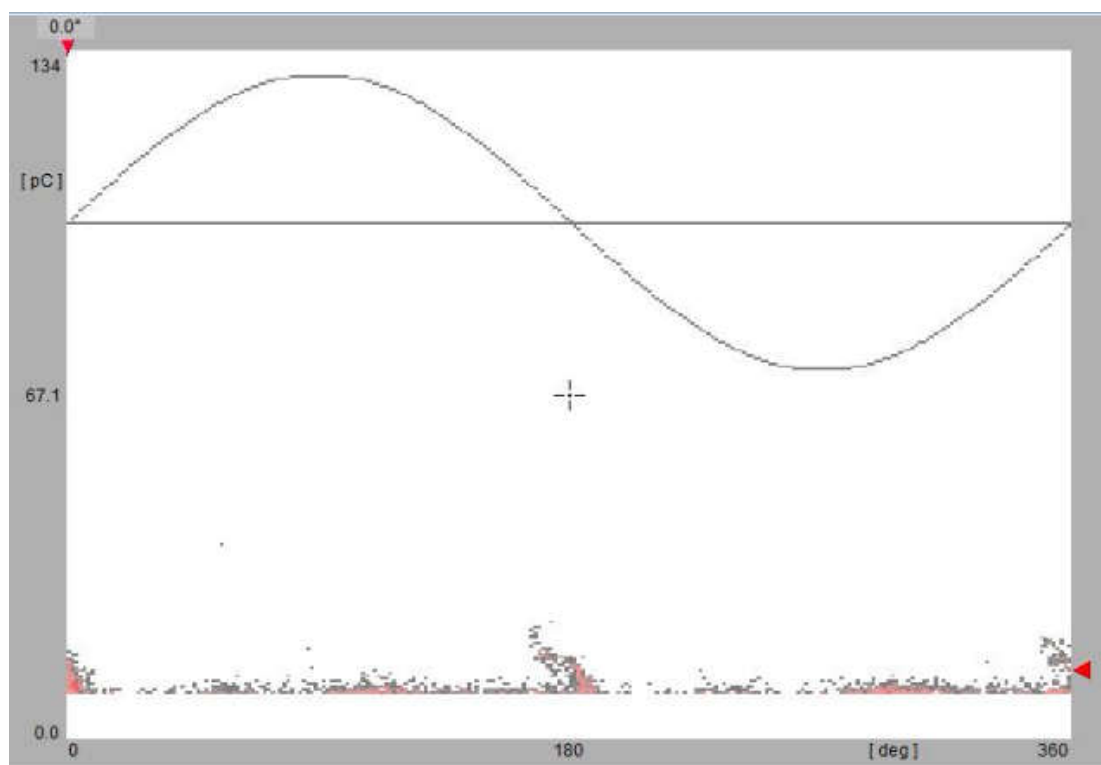
(c) 9,47 pC at 150 kV

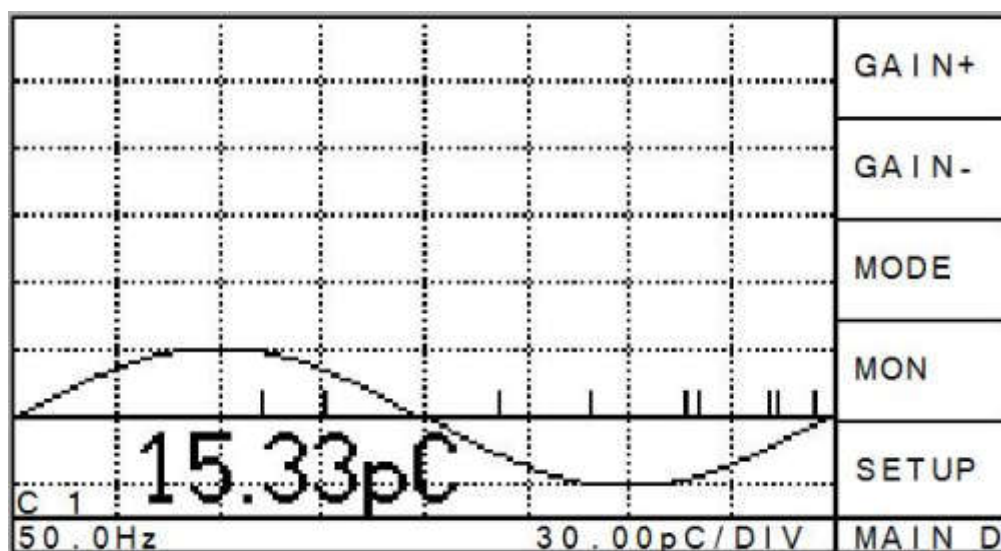PRPD pattern measured on a 300 kV transformer.

Annexure K: Partial discharge measurement using CT100
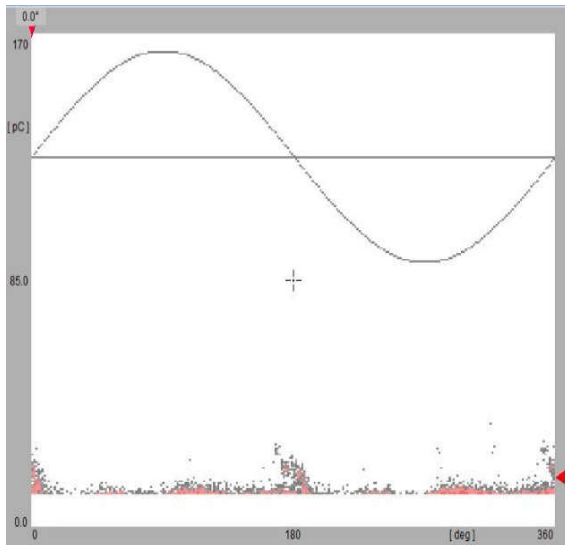

(a) 13,33 pC at 50 kV

(b) 13,33 pC at 100 kV

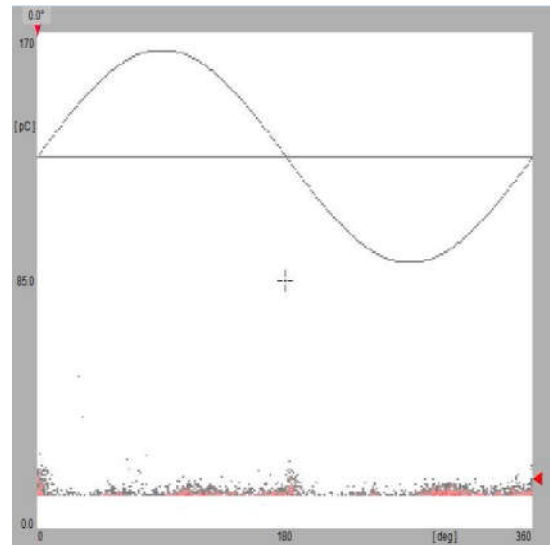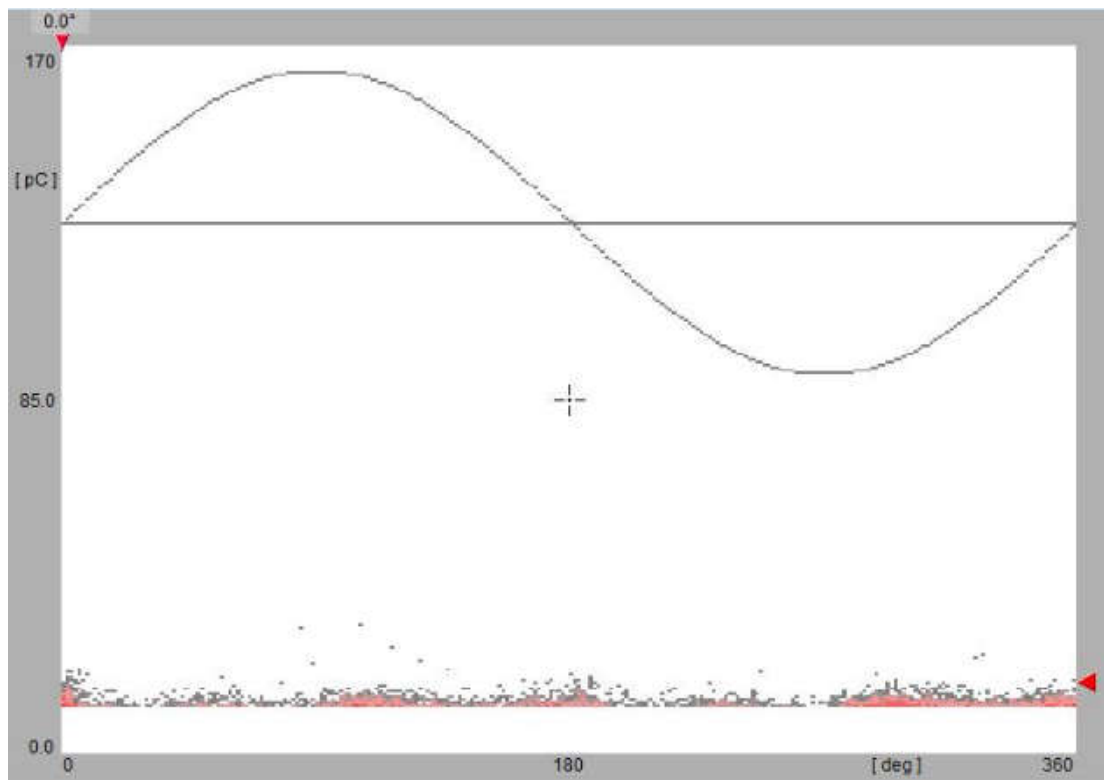(c) 15,33 pC at 150 kV

PD pulses recorded from a 300 kV transformer.

(a) 13,33 pC at 50 kV   (b) 13,33 pC at 100 kV

(c) 15,33 pC at150 kV

PRPD pattern measured on a 300 kV transformer.